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Technology Trends, Threats, Requirements, and Opportunities (T^3R&O) Study on Advanced Power Sources for the Canadian Forces in 2020

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Defence Research & Development Canada

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ABSTRACT

In this study, the state-of-the-art and current trends in a broad range of advanced power source technologies of interest for future CF requirements has been assessed. The power source technologies examined include electrochemical power sources, electromechanical power sources, micro-electromechanical power sources, renewable energy sources, nuclear sources and energy storage technologies. The report examines the ability of these advanced power sources to meet CF requirements out to the year 2020 and identifies specific research and development opportunities that exist for DRDC. Based on these opportunities, an expanded R&D program in the Advanced Power Source area has been proposed. The principal elements of the proposed program include work in the areas of: Materials and manufacturing technology for fuel cells and batteries; hydrogen storage and production technologies; and, pulse power technologies.

RÉSUMÉ

Dans cette étude, on a évalué les tendances actuelles d'une vaste gamme de technologies des sources d'énergie avancées qui sont d'intérêt pour les futures Forces canadiennes. On a notamment étudié les sources d'énergie électrochimique, électromécanique et micro-électromécanique; les sources d'énergie renouvelables; les sources nucléaires et les technologies de stockage d'énergie. Le rapport analyse la tendance de ces sources d'énergie avancées à remplir les besoins des FC jusqu'à l'an 2020 et met en lumière les possibilités de recherche-développement qu'offre RDDC. En s'inspirant de ces possibilités, on a proposé un programme R-D élargi relatif aux sources d'énergie avancées. Le programme comprend principalement des travaux sur : les matériaux et la technologie servant à fabriquer des piles et des batteries de piles à combustible; les technologies de stockage et de production d'hydrogène; les technologies de la puissance à impulsions.

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EXECUTIVE SUMMARY

Based on the expected changes to military operations up to the year 2020, this report examines the current and future trends in advanced power sources (APS).

Military operations, both strategic and tactical, will be increasingly dependent on electronic and electrical systems to support various functions, including Command, Sense, Act, Shield, and Sustain functions. Improved power sources will be required for sensors and generator sets as well as for electric guns and directed energy weapons. There are also many rapidly emerging trends in military technology including hybrid electric military vehicles, all electric ships and power for soldier systems whose success will depend on the availability of sufficient electrical power.

Electrical power can be derived from a variety of sources including electrochemical sources (e.g. batteries and fuel cells), electromechanical sources (e.g. engine generators and thermoelectric generators), renewable energy sources (e.g. solar and wind), and nuclear sources (e.g. nuclear submarine power plants). Hybrid power sources can be used to obtain the best properties of two or more power sources and are expected to become an essential element for future battlespace operation. Power source performance can be significantly degraded due to environmental conditions such as temperature, humidity, solar intensity, contaminants in the air, fuel quality, and user abuse.

No single power source technology is capable of meeting all of the Canadian Forces (CF) power requirements ranging from the microwatts needed to power microelectromechanical system (MEMS) sensors to the megawatts required for ship and vehicle propulsion as illustrated in Figure E1. It is important, however, that, in order to minimize problems related to supply, logistics and interoperability with our Allies, the proliferation of power source types and fuels should be kept to a minimum. In contrast, the telecom and electronic industries appear to have adopted a strategy of developing and packaging a custom power source for every specific application. Adopting such a commercial practice for military power sources could create proliferation of too many variants of power packs which could impose significant logistic, reliability, interoperability, and supportability difficulties, resulting in unacceptable operational, safety and financial risks.

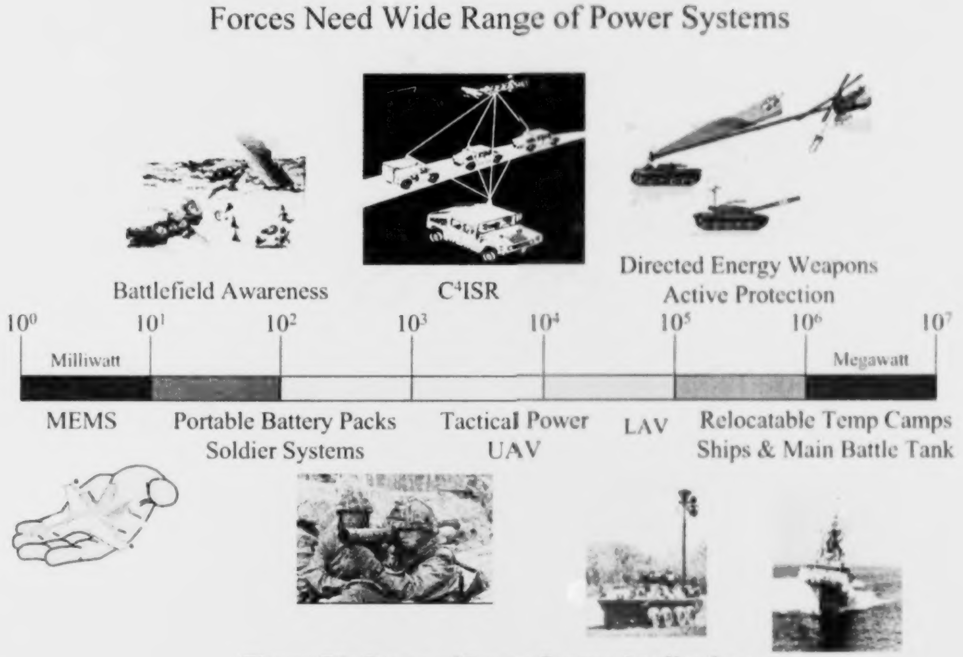
Forces Need Wide Range of Power Systems
Battlefield Awareness
C4ISR
Directed Energy Weapons
Active Protection
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Milliwatt
Megawatt
MEMS
Portable Battery Packs
Soldier Systems
Tactical Power
UAV
LAV
Relocatable Temp Camps
Ships & Main Battle Tank

Figure E1: Range of Power Source Applications

The aim of this study, entitled “Technology Trends, Threats, Requirements and Opportunities ($T^3R\&O$) on Advanced Power Sources for the Canadian Forces in 2020”, is to evaluate those power sources that have the capability of meeting future military requirements, to find the existing technology gaps and to identify research and development (R&D) opportunities. The results of this study are presented in this report.

Chapter 1 outlines the scope of the study and describes the methodology used to identify potential power sources, their capability gaps and R&D opportunities.

Chapter 2 describes the battlespace technology trends that are expected in the future. This analysis was based on Department of National Defence (DND) and Royal Military College (RMC) studies, NATO Research and Technology Organization (RTO) studies as well as studies produced by the US and other Allies outlining future military concepts. Important trends in military technology that are expected to influence future CF operations include information assurance and total battlespace awareness, improved mobility, increased weapon lethality and widespread introduction of stealth technology. A set of power source requirements has been derived taking these trends into account. This selection is considered to be representative for the range of power source requirements that the CF will have in the future.

While some power source requirements are specific to each element, a large number of them are "joint" requirements, hence common to all of the elements (Figure E2). The best return on technology investment appears to be on those with “joint” interest. However, the individual elements will also need power sources to meet their specific needs. The failure to develop power sources that meet the needs of emerging military systems could pose unacceptable risks to weapon system development and life cycle support.

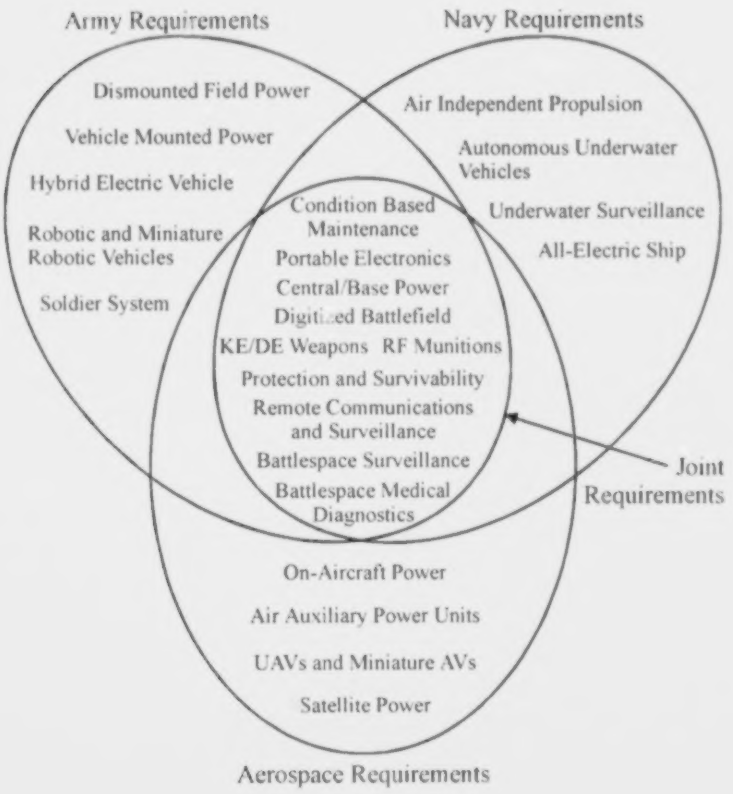
Army Requirements
Navy Requirements
Dismounted Field Power
Vehicle Mounted Power
Hybrid Electric Vehicle
Robotic and Miniature Robotic Vehicles
Soldier System
Air Independent Propulsion
Autonomous Underwater Vehicles
Underwater Surveillance
All-Electric Ship
Condition Based Maintenance
Portable Electronics
Central/Base Power
Digitized Battlefield
KE/DE Weapons
RF Munitions
Protection and Survivability
Remote Communications and Surveillance
Battlespace Surveillance
Battlespace Medical Diagnostics
Joint Requirements
On-Aircraft Power
Air Auxiliary Power Units
UAVs and Miniature AVs
Satellite Power
Aerospace Requirements

Figure E2: User Requirements

Chapter 3 presents the current state-of-the-art of the various power source technologies of interest, discusses future trends in these technologies and identifies research and development opportunities. To assist in the identification and evaluation on R&D opportunities, all of the power source technologies were put through a series of "filters" to assess whether the power source has potential to meet the requirement and to select the most promising R&D opportunities.

Chapter 4 analyzes the R&D opportunities identified in the previous chapter and makes recommendations for technology investment. Some of the results are shown in Table E1. In this table, the power source requirements have been sub-divided into four general power ranges. The general characteristics of each of the requirements as well as power source options are also presented. Table E2 presents some of the specific R&D opportunities that have been identified and gives some detail of the delivery timeframe that has been proposed.

Depending on the requirement, each characteristic of a power source has a different priority. As shown in Table E2, various types of power source technologies are available for each requirement, but the challenge is to select those technologies that are (easily) scalable to suit various military systems. This selection method does not eliminate power sources needed for special applications.

Conclusions

By the year 2020, military technology will include kinetic and directed energy weapons and electrically propelled ships, land weapon platforms and micro air vehicles. The electromagnetic spectrum will be occupied with wireless networks and sensor information generated from the Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) systems, and that spectrum will be defended by electromagnetic denial and deceptive systems. New military technologies will provide the theatre of operations with excellent Command, Sense, Act, Shield, and Sustain capabilities. It is envisaged, however, that many of these advanced military systems will not be able to deliver their full capabilities if suitable power sources are not developed in parallel with other advanced technologies.

Recommendations

Current power sources can be further improved and will still stay in service for a significant time, but emerging technologies such as fuel cells, hybrid and regenerative systems, power MEMS and specialty electromechanical power devices have the potential to provide better power and energy densities as well as other improved characteristics (e.g. signatures, fuel efficiency) over the existing products. The advancement in these power source technologies will assist military planners and system developers to introduce new military equipment.

It is also highly desirable to develop power source technologies that allow energy harvesting from the environment. These technologies will increase output capacity and endurance by allowing the main power source to be recharged with renewable energy such as solar, or with fuels that can be reconstituted in the theatre such as hydrogen. The use of renewable energy sources can potentially extend mission time while reducing supply logistics.

To meet future CF power source requirements, this report identifies significant R&D opportunities in the following three areas:

1. Materials and Manufacturing Technologies for Fuel Cells and Batteries:
   Work in this area would include the investigation of microfabrication techniques for the production of batteries and fuel cells, nanomaterials to improve battery performance and new fuel cell electrocatalysts and membranes to improve power output and tolerance to battlefield contaminants.

2. Hydrogen Storage and Production:
   Work in this area would include the investigation of carbon- and other nanomaterials for hydrogen storage and the reforming of logistic fuels as well as the use of chemical hydrides and bio-synthesis for hydrogen production.

3. Pulse Power Technologies:
   Work in this area would include the investigation of high power pulse forming devices and explosively driven magnetocumulative generators.

Not only the lack of adequate power sources, but also the proliferation of power sources not supported by the logistics chain as well as the reliance on commercial-off-the-shelf power sources could pose significant risks in the areas of performance, sustainment and safety or could even jeopardize a mission. Therefore, to minimize the risk of fielding wrong power sources to the theatre and to have the ability to provide emergency response, sound management and knowledgeable personnel on advanced power sources are required. It would be advantageous to establish a Tri-

Service Advanced Power Sources Knowledge Centre within DND consisting of scientists, engineers, logisticians, and life cycle managers to advise the departmental staff and execute APS projects of CF interest and to coordinate the effort for the CF to achieve efficiency and cost effectiveness.

Since advanced power sources will be required for all electrically operated systems, it is imperative for the CF to examine the power source issue and to fill potential gaps that might hinder advancement in battlefield technologies and mission capabilities.

Acronyms used in Figures E1 and E2 and in Tables E1 and E2

AIP	Air Independent Propulsion
AV	Autonomous Vehicle
C^4ISR	Communication, Command & Control, Computers, Intelligence, Surveillance and Reconnaissance
CF	Canadian Forces
CO	Carbon (Mon)oxide
DE	Direct Energy
DMFC	Direct Methanol Fuel Cell
EM	Electromagnetic
EMG	Explosive Driven Magnetocumulative Generator
JP4	Jet Fuel
KE	Kinetic Energy
LAV	Light Armored Vehicle
LT	Low Temperature
MCG	Magnetocumulative Generator
MEMS	Micro Electromechanical System
PEMFC	Polymer Electrolyte Membrane Fuel Cell
PFN	Pulse Forming Network
RF	Radio Frequency
SOFC	Solid Oxide Fuel Cell
TEG	Thermoelectric Generator
TPV	Thermo Photovoltaic
UAV	Unmanned Autonomous Vehicle

Table E1: Classification of and Power Source Options for CF Requirements

POWER RANGE	REQUIREMENTS	CHARACTERISTICS	POWER SOURCE OPTIONS
Micro Power (µW – 100 mW)	Sensors and Actuators	Microscopic scale High energy density/long endurance Environmentally friendly Energy harvesting desirable	Micro Batteries Micro Fuel Cells Micro TEG Micro TPV generators Piezoelectric Micro Engines
Low Power (100 mW – 100 W)	Integrated Wearable Power	Extremely high energy density Highly efficient Low signature Safe and maintenance-free Low life cycle costs Energy harvesting desirable	DMFC Hydride Fueled PEMFC TPV Generator Micro Engine
	Portable Power	High energy density Compact/lightweight Low signature Non-polluting /low cost Long cycle life	Primary Batteries Secondary Batteries DMFC Hydride Fueled PEMFC
	Miniature Robotics	High energy density Maintenance free Low signature Reliable	Batteries Fuel Cells Microfabricated Fuel Cells TPV Generator Micro Engine
Medium Power (100 W – 100 kW)	Mounted/Mobile Power	Compact/lightweight Safe/easy-to-use Low fuel consumption Rugged/reliable Interoperability Continuous availability	Engine Generators Diesel Fueled SOFC PEM Fuel Cell Solar/Battery
	Aerospace Power	High energy density Compact/lightweight Reliable/safe	Secondary Batteries Primary Batteries Fuel Cells
	Remote Power	Highly reliable Low fuel consumption Maintenance-free Energy harvesting desirable	Solar Hybrid Systems Batteries Thermoelectric Generators
High Power (100 kW – 10 GW)	Vehicle Propulsion	High energy and power density Rugged/Safe Compact/lightweight Low fuel consumption Suitable for mil. environmental conditions Interoperability	Engines Diesel Fueled SOFC PEM Fuel Cells Hydrogen Storage Diesel Reforming Secondary Batteries
	Central Power	Low fuel consumption Low life-cycle costs Easy to use and to maintain Long MTBF, short MTTR Interoperability	Hydro Nuclear Magnetohydrodynamics Renewable Energy Sources
	Pulse Power	High energy and extremely High power density Compact Rugged	Mechanical Energy Storage EM Storage Explosive MCGs Piezoelectric Generators

Table E2: Linkages of Power Source Requirements to S&T Opportunities and Delivery Timeframe

Applications	**Power Source Options**	**S&T Opportunities**	**Delivery Timeframe**		
			Short	Mid	Long
Soldier System	- Fuel cells and micro fuel cells - Thermophotovoltaic generator - Micro engines	- improved power density and LT performance of direct methanol fuel cells		X	
		- increased efficiency of DMFC by reducing methanol cross-over			X
		- high energy density hydrogen storage for soldier system and AIP requirements			X
		- chemical hydride generator for compact PEMFC for soldier system	X		
Tactical, Mobile Electrical Power	- Fuel cells - Thermophotovoltaic generator - Solar	- battlefield contaminant resistant electrocatalysts for PEMFC		X	
		- CO tolerant catalysts for PEMFC	X		
		- SOFC capable of using logistic fuels for tactical power		X	
		- compact hydrogen generator capable of low temperature operation and rapid start-up		X	
		- hydrogen production from logistic fuels (Diesel/JP4)			X
Power for Distributed Sensors and Actuators	- Microbatteries - Micro Fuel Cells - Micro Engines - Micro Thermoelectric Generators - Micro Photovoltaics	- micro fuel cells and batteries for MEMS sensors and actuators			X
Portable Electronics	- Primary Batteries - Secondary Batteries - fuel cells	- Lithium pouch batteries functional to - 40C		X	
		- Lithium battery/supercapacitor hybrids for high power applications	X		
Remote Power for Communications and Surveillance	- Batteries - Photovoltaic Hybrid Systems - Thermoelectric Generators	- improved rechargeable batteries for solar energy storage - improved efficiency thermoelectric materials - liquid fueled thermoelectric generators for remote applications	X	X	X
Kinetic Energy and Radio Frequency Weapons	- Mechanical Energy Storage - Electrical Energy Storage	- compact hydrogen generator capable of low temperature operation and rapid start-up	X		
		- impedance matching/load switching of PFN to KE and RF loads		X	
RF Munitions	- Explosive Magnetocumulative Generator - Piezoelectric Pulse Generators	- compact EMG development	X		
		- impedance matching/load switching of PFN to KE and RF loads		X	

All-Electric Vehicle	- Engine Generators - Fuel Cells - Mechanical energy Storage - Supercapacitors - pulse power source	- battlefield contaminant resistant electrocatalysts for PEMFC		X	
		- SOFC capable of using logistic fuels for tactical power		X	
		- compact hydrogen generator capable of low temperature operation and rapid start-up		X	
		- hydrogen production from logistic fuels (Diesel/JP4)	X		X
		- pulse power demonstration system for all-electric vehicle			
All-Electric Ship	- Engines - Fuel Cells	- CO tolerant catalysts for PEMFC	X		
		- SOFC capable of using logistic fuels for tactical power		X	
		- hydrogen production from logistic fuels (Diesel/JP4)			X
Micro Air Vehicles and Micro Robots	- Batteries - Fuel Cells And Microfabricated Fuel Cells - Thermophotovoltaic Generator - micro engines	- Improved power density and LT performance of direct methanol fuel cells		X	
		- increased efficiency of DMFC by reducing methanol cross-over			X
Air Independent Propulsion of Submarines and Submersibles	- Fuel cells - Batteries - Nuclear Power	- CO tolerant catalysts for PEMFC	X		
		- high energy density hydrogen storage for soldier system and AIP requirements			X
		- AIP demonstrator using methanol reformation	X		
		- hydrogen production from logistic fuels (Diesel/JP4)			X
Central Power	- Hydro - Nuclear - Magnetohydrodynamics - Renewable Energy Sources	- SOFC capable of using logistic fuels for tactical power		X	
		- hydrogen production from logistic fuels (Diesel/JP4)			X

SOMMAIRE

Basé sur les changements prévus des opérations militaires d'ici l'an 2020, ce rapport examine les tendances actuelles et futures des sources d'alimentation de pointe (SAP).

Les opérations militaires, tant stratégiques que tactiques, dépendront de plus en plus de systèmes électroniques et électriques pour prendre en charge diverses fonctions, y compris les fonctions de commandement, de détection, de capture, de protection et de soutien. Des sources d'alimentation améliorées seront nécessaires pour les capteurs et les groupes électrogènes ainsi que pour les canons électriques et les armes à énergie dirigée. De plus, il y a de nombreuses tendances émergeant rapidement dans la technologie militaire, y compris véhicules militaires électriques hybrides, navires tout électriques et alimentation de systèmes du soldat, dont le succès dépendra de la suffisance d'énergie électrique disponible.

L'énergie électrique peut être dérivée de diverses sources, à savoir des sources électrochimiques (p. ex. batteries et piles à combustible), des sources électromécaniques (p. ex. groupes électrogènes et convertisseurs thermoélectriques), des sources d'énergie renouvelables (p. ex. solaires et éoliennes) et des sources nucléaires (p. ex. groupes de propulsion nucléaires de sous-marin). Des sources d'alimentation hybrides peuvent être utilisées pour mettre en valeur les meilleures caractéristiques de deux ou plusieurs sources d'alimentation et on s'attend à ce qu'elles deviennent un élément essentiel des opérations futures dans l'espace de combat. Les performances des sources d'alimentation peuvent être dégradées considérablement par les conditions environnementales, telles que la température, l'humidité, l'intensité solaire, les polluants dans l'air, la qualité du combustible et un mauvais usage par l'utilisateur.

Aucune technologie de source d'alimentation particulière n'est capable de répondre à tous les besoins en énergie des Forces canadiennes (FC), allant des microwatts nécessaires à l'alimentation des capteurs de système micro-électromécanique (MEMS) aux mégawatts nécessaires à la propulsion des navires et des véhicules (voir figure E1). Cependant, il importe de limiter autant que possible la prolifération des types de sources d'alimentation et de combustibles, afin de réduire au minimum les problèmes relatifs à l'approvisionnement, à la logistique et à l'interopérabilité avec nos alliés. En revanche, les industries des télécommunications et de l'électronique semblent avoir adopté une stratégie de développement et de conditionnement d'une source d'alimentation propre à chaque application particulière. L'adoption d'une telle pratique commerciale pour les sources d'alimentation militaires risque d'entraîner la prolifération des variantes de blocs d'alimentation, ce qui risque de provoquer des problèmes considérables de logistique, de fiabilité, d'interopérabilité et de soutenabilité, ce qui mènerait à des risques opérationnels, sécuritaires et financiers inacceptables.

Cette étude, intitulée « Technology Trends, Threats, Requirements and Opportunities ($T^3R\&O$) on Advanced Power Sources for the Canadian Forces in 2020 », a pour but d'évaluer les sources d'alimentation capables de répondre aux exigences militaires futures, de déterminer les lacunes des technologies existantes et de relever les possibilités de recherche et développement (R-D). Les résultats de cette étude font l'objet du présent rapport.

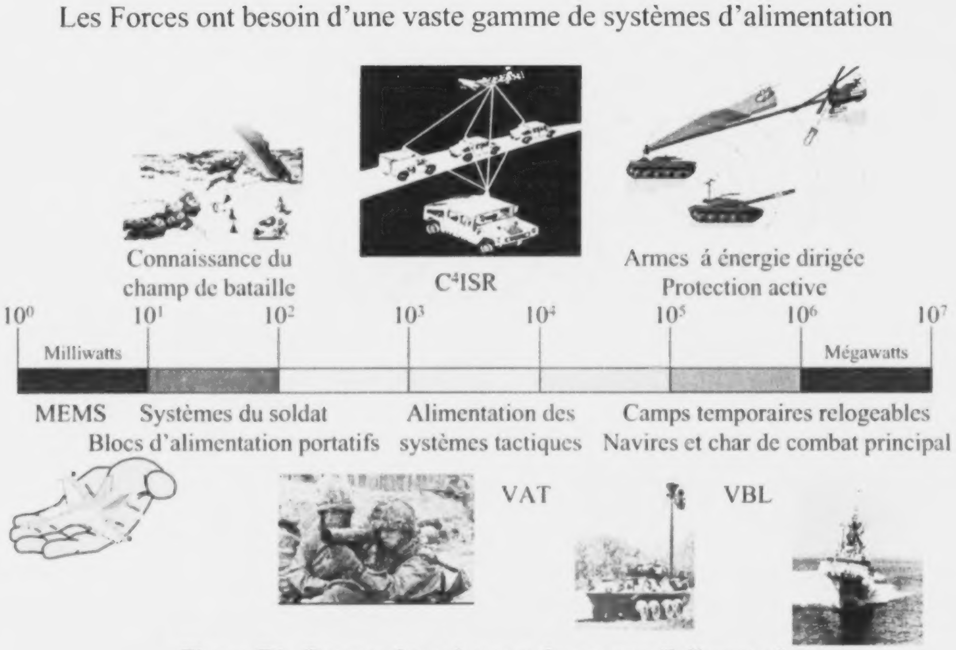
Les Forces ont besoin d'une vaste gamme de systèmes d'alimentation
Connaissance du champ de bataille
C4ISR
Armes á énergie dirigée
Protection active
10⁰
10¹
10²
10³
10⁴
10⁵
10⁶
10⁷
Milliwatts
Mégawatts
MEMS
Systèmes du soldat
Blocs d'alimentation portatifs
Alimentation des systèmes tactiques
Camps temporaires relogeables
Navires et char de combat principal
VAT
VBL

Figure E1: Gamme des exigences de sources d'alimentation

Le chapitre 1 décrit la portée de l'étude et la méthode utilisée pour identifier des sources d'alimentation potentielles, les lacunes de leurs capacités et les possibilités de R-D.

Le chapitre 2 décrit les tendances de la technologie de l'espace de combat prévues pour l'avenir. Cette analyse était basée sur des études du ministère de la Défense nationale (MDN), du Collège militaire royal (CMR), de l'Organisation de recherche et de technologie (ORT) de l'OTAN ainsi que sur des études élaborées par les É.-U. et d'autres alliés esquissant des concepts militaires futurs. Les tendances importantes en technologie militaire dont on prévoit l'influence sur les opérations futures des FC comprennent l'assurance de l'information, la connaissance parfaite de l'espace de combat, l'amélioration de la mobilité, une plus grande létalité des armes et l'introduction généralisée de la technologie de discrétion. On a dérivé une série d'exigences pour les sources d'alimentation qui tiennent compte de ces tendances. On considère que les exigences sélectionnées sont représentatives de la gamme d'exigences relatives aux sources d'alimentation que les FC auront à l'avenir.

Certaines exigences relatives aux sources d'alimentation sont propres à chaque force, mais un grand nombre d'entre elles sont des exigences interarmées, de sorte qu'elles sont communes à toutes les forces (figure E2). Les meilleurs dividendes des investissements dans la technologie semblent correspondre aux exigences « interarmées ». Cependant, les forces individuelles auront également besoin de sources d'alimentation répondant à leurs besoins particuliers. Si l'on ne réussit pas à développer des sources d'alimentation qui répondent aux besoins des systèmes militaires en émergence, cela risque de poser des risques inacceptables pour le développement et le soutien de cycle de vie de systèmes d'armes.

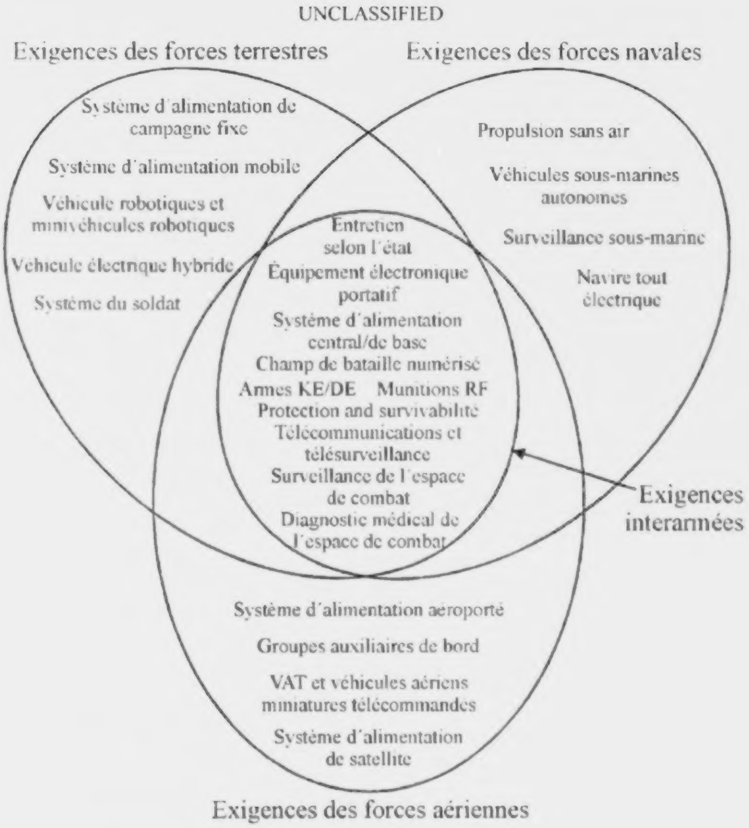
UNCLASSIFIED
Exigences des forces terrestres
Exigences des forces navales
Système d'alimentation de campagne fixe
Système d'alimentation mobile
Véhicule robotiques et minivéhicules robotiques
Véhicule électrique hybride
Système du soldat
Propulsion sans air
Véhicules sous-marines autonomes
Surveillance sous-marine
Navire tout électrique
Entretien selon l'état
Équipement électronique portatif
Système d'alimentation central/de base
Champ de bataille numérisé
Armes KE/DE
Munitions RF
Protection and survivabilité
Télécommunications et télésurveillance
Surveillance de l'espace de combat
Diagnostic médical de l'espace de combat
Exigences interarmées
Système d'alimentation aéroporté
Groupes auxiliaires de bord
VAT et véhicules aériens miniatures télécommandés
Système d'alimentation de satellite
Exigences des forces aériennes

Figure E2: Exigences des utilisateurs

Le chapitre 3 présente l'état actuel des diverses technologies des sources d'alimentation d'intérêt, traite des tendances futures de ces technologies et identifie les possibilités de recherche et développement. Pour faciliter l'identification et l'évaluation de possibilités de R-D, toutes les technologies de source d'alimentation ont été appliquées à une série de « filtres » pour déterminer si la source d'alimentation a le potentiel de répondre au besoin et pour sélectionner les possibilités de R-D les plus prometteuses.

Le chapitre 4 analyse les possibilités de R-D identifiées au chapitre précédant et fait des recommandations d'investissement dans la technologie. Certains des résultats figurent au tableau E1. Dans ce tableau, les exigences relatives aux sources d'alimentation ont été divisées en quatre gammes de puissance générales. On y trouve également les caractéristiques générales de chacune des exigences ainsi que les options de source d'alimentation. Le tableau E2 donne certaines des possibilités de R-D particulières qui ont été identifiées et donne une indication du délai de réalisation proposé.

Tout dépendant de l'exigence, chaque caractéristique d'une source d'alimentation a une priorité différente. Comme le montre le tableau E2, divers types de technologies de source d'alimentation sont disponibles pour chaque exigence, mais le défi consiste à sélectionner les technologies qui sont (facilement) échelonnables en fonction des divers systèmes militaires. Cette méthode de sélection n'élimine pas les sources d'alimentation nécessaires pour des applications spéciales.

Conclusions

D'ici l'an 2020, la technologie militaire comprendra des armes à énergie cinétique et à énergie dirigée ainsi que des navires, des plates-formes d'armes terrestres et des micro-aéronefs à propulsion électrique. Le spectre électromagnétique sera occupé par des réseaux sans fil et de l'information de détection générée par des systèmes de renseignements, de surveillance, d'acquisition d'objectif et de reconnaissance (ISTAR) et il sera défendu au moyen de systèmes électromagnétiques de déception et d'interdiction d'accès. De nouvelles technologies militaires fourniront au théâtre des opérations d'excellentes capacités de commandement, de capture, d'action, de protection et de soutien. Cependant, on prévoit que bien de ces systèmes militaires de pointe ne seront pas capables de mettre en valeur leur plein potentiel si des sources d'alimentation appropriées ne sont pas développées de pair avec les autres technologies de pointe.

Recommandations

Les sources d'alimentation existantes permettent des améliorations et demeureront en service pendant une période considérable, mais les technologies en émergence telles que les piles à combustible, les systèmes hybrides et régénératifs, les systèmes MEMS d'alimentation et les dispositifs d'alimentation électromécaniques spécialisés ont le potentiel de produire des densités de puissance et d'énergie supérieures ainsi que d'autres caractéristiques améliorées (p. ex. signatures, efficience énergétique) par rapport aux produits existants. Les progrès de ces technologies de source d'alimentation aideront les planificateurs et développeurs de systèmes militaires à introduire de nouveaux appareils militaires.

De plus, il est fort souhaitable d'élaborer des technologies de source d'alimentation qui permettent de capturer l'énergie de l'environnement. Ces technologies augmenteront la puissance nette et la viabilité en permettant à la source d'alimentation principale de se recharger d'énergie renouvelable telle que l'énergie solaire, ou de combustibles qui peuvent être reconstitués sur le théâtre des opérations tels que l'hydrogène. L'utilisation de sources d'énergie renouvelables a le potentiel d'augmenter le temps consacré à la mission tout en réduisant la logistique d'approvisionnement.

En vue de répondre aux exigences futures des sources d'alimentation des FC, ce rapport identifie des possibilités considérables de R-D dans les domaines suivants :

1. Technologies des matériaux et de la fabrication de piles à combustible et de batteries:
   Le travail dans ce domaine comprendrait l'étude de techniques de microfabrication pour la production de batteries et de piles à combustible, de nanomatériaux pour améliorer les performances des batteries et de nouveaux électrocatalyseurs et membranes pour piles à combustible pour améliorer la puissance nette et la tolérance aux polluants du champ de bataille.

2. Stockage et production d'hydrogène:
   Le travail dans ce domaine comprendrait l'étude du carbone - et d'autres nanomatériaux - pour le stockage de l'hydrogène et le reformage de combustibles de logistique ainsi que l'utilisation d'hydrures et de la biosynthèse pour la production d'hydrogène.

3. Technologies d'alimentation pulsée:
   Le travail dans ce domaine comprendrait l'étude de dispositifs de génération d'impulsions haute puissance et de générateurs magnétocumulatifs à explosion.

Tant le manque de sources d'alimentation adéquates que la prolifération de sources d'alimentation non soutenues par la chaîne logistique ainsi que la confiance accordée aux sources d'alimentation commerciales courantes pourraient poser des risques considérables dans les domaines des performances, du soutien et de la sécurité, voire compromettre une mission. Par conséquent, en vue de réduire au minimum le risque de distribuer les mauvaises sources d'alimentation au théâtre et d'avoir la capacité d'assurer l'intervention en cas d'urgence, il faut une gestion saine et du personnel compétent en matière de sources d'alimentation de pointe. Il serait avantageux d'établir au sein du MDN un centre interarmées de connaissances en sources d'alimentation de pointe qui comprendrait des scientifiques, des ingénieurs, des logisticiens et des gestionnaires de cycle de vie qui fourniraient des conseils au personnel du Ministère et exécuteraient des projets SAP d'intérêt pour les FC et qui coordonneraient l'effort des FC à réaliser l'efficience et la rentabilité.

Comme des sources d'alimentation de pointe seront nécessaires à tous les systèmes électriques, il est impératif que les FC examinent la question des sources d'alimentation et comblent les lacunes éventuelles qui risquent de gêner le progrès des technologies de champ de bataille et des capacités de mission.

Acronymes utilisés aux figures E1 et E2 et aux tableaux E1 et E2

BT	Basse température
C^{4}ISR	Communication, commandement et contrôle, ordinateurs, renseignement, surveillance et reconnaissance
CO	Monoxyde de carbone
DMFC	Pile à combustible directe au méthanol
FC	Forces canadiennes
JP4	Carburant aviation
KE	Énergie cinétique
MCG	Générateur magnétocumulatif
MEMS	Système micro-électromécanique
PEMFC	Pile à combustible à membrane à électrolyte polymérique
PSA	Propulsion sans air
RCI	Réseau conformateur d'impulsions
RF	Radiofréquence
SOFC	Pile à combustible à oxyde solide
VAT	Véhicule aérien télécommandé
VBL	Véhicule blindé léger

Tableau E1: Classification des sources d'alimentation et options pour les besoins des FC

GAMME DE PUISSANCE	EXIGENCES	CARACTÉRISTIQUES	OPTIONS DE SOURCE D'ALIMENTATION
Micropuissance (µW – 100 mW)	Capteurs et actionneurs	Échelle microscopique Haute densité énergétique/ grande endurance Écologique Capture d'énergie souhaitable	Microbatteries Micropiles à combustible Microconvertisseur thermoélectrique Microgénérateurs thermophotovoltaïques Micromoteurs piézoélectriques
Faible puissance (100 mW – 100 W)	Bloc d'alimentation vêtement	Très haute densité énergétique Très efficace Signature faible Sûr et sans entretien Coûts de cycle de vie réduits Capture d'énergie souhaitable	DMFC PEMFC alimentées en hydrure Générateurs thermophotovoltaïques Micromoteurs
	Bloc d'alimentation portatif	Haute densité énergétique Compact/léger Signature faible Écologique/économique Longue durée de vie	Batteries primaires Batteries secondaires DMFC PEMFC alimentées en hydrure
	Robotique miniaturisée	Haute densité énergétique Sans entretien Signature faible Fiable	Batteries Piles à combustible Piles à combustible microfabriquées Générateurs thermophotovoltaïques Micromoteurs
Moyenne puissance (100 W – 100 kW)	Système d'alimentation fixe/mobile	Compact/léger Sûr/facile à utiliser Faible consommation de combustible Robuste/fiable Interopérabilité Disponibilité continue	Groupes électrogènes SOFC alimentées en combustible Diesel PEMFC Batteries solaires
	Système d'alimentation aérospatial	Haute densité énergétique Compact/léger Fiable/sûr	Batteries secondaires Batteries primaires Piles à combustible
	Système d'alimentation éloigné	Très fiable Faible consommation de combustible Sans entretien Capture d'énergie souhaitable	Systèmes solaires hybrides Batteries Convertisseurs thermoélectriques
Haute puissance (100 kW – 10 GW)	Propulsion de véhicules	Haute densité énergétique et de puissance Robuste/sûr et compact/léger Faible consommation de combustible Convenant aux conditions environnementales militaires Interopérabilité	Moteurs SOFC alimentées en combustible Diesel PEMFC Stockage d'hydrogène Reformage de combustible diesel Batteries secondaires
	Centrale d'énergie	Faible consommation de combustible Coûts de cycle de vie réduits Facile à utiliser et à maintenir Grande MTBF, MTTR réduite Interopérabilité	Hydroélectrique Nucléaire Magnétohydrodynamique Sources d'énergie renouvelables
	Alimentation pulsée	Haute densité énergétique et très haute densité de puissance Compact Robuste	Stockage d'énergie mécanique Stockage d'énergie électromagnétique MCG à explosions Générateurs piézoélectriques

Tableau E2: Liens entre les exigences de sources d'alimentation et les possibilités de R-D avec délai de réalisation

Exigence	Options de source d'alimentation	Possibilités de R-D	Délai de réalisation		
			Court	Moy.	Long
Système du soldat	- Piles à combustible et micropiles à combustibles - Générateur thermophotovoltaïque - Micromoteurs	- amélioration de la densité de puissance et des performances BT des piles à combustible directes au méthanol		X	
		- augmentation du rendement de la DMFC en réduisant la traversée du méthanol			X
		- stockage d'hydrogène à haute densité énergétique pour les exigences de système du soldat et de propulsion sans air			X
		- générateur d'hydrure pour PEMFC compact de système du soldat	X		
Système d'alimentation électrique tactique mobile	- Piles à combustible - Générateur thermophotovoltaïque - Énergie solaire	- électrocatalyseurs pour PEMFC, résistants aux polluants du champ de bataille		X	
		- catalyseurs pour PEMFC, tolérants au CO	X		
		- SOFC capable d'utiliser des combustibles logistiques pour l'alimentation de systèmes tactiques		X	
		- générateur d'hydrogène compact à démarrage rapide et capable de fonctionner à basse température		X	
		- production d'hydrogène à partir de combustibles de logistique (Diesel/JP4)			X
Alimentation de capteurs et actionneurs répartis	- Microbatteries - Micropiles à combustible - Micromoteurs - Microconvertisseurs thermoélectriques - Microgénérateurs photovoltaïques	- micropiles à combustible et microbatteries pour les capteurs et actionneurs MEMS			X
Matériel électronique portatif	- Batteries primaires - Batteries secondaires - Piles à combustible	- piles au lithium en pochette utilisables jusqu'à -40 °C		X	
		- combinaisons pile au lithium/supercondensateur pour les applications à haute puissance	X		
Équipement éloigné de communication et de surveillance	- Batteries - Systèmes photovoltaïques hybrides - Convertisseurs thermoélectriques	- amélioration de batteries rechargeables pour le stockage d'énergie solaire			X
		- amélioration du rendement de matériaux thermoélectriques		X	
		- convertisseurs thermoélectriques à combustible liquide pour applications éloignées	X		
Armes à énergie cinétique et radiofréquence	- Stockage d'énergie mécanique - Stockage d'énergie électrique	- générateur d'hydrogène compact à démarrage rapide et capable de fonctionner à basse température	X		
		- adaptation d'impédance/commutation de charge de RCI avec des charges KE et RF		X	

Munitions RF	- Générateur magnétocumulatif à explosion - Générateurs d'impulsions piézoélectriques	- développement d'un générateur électromagnétique compact	X		
		- adaptation d'impédance/commutation de charge de RCI avec des charges KE et RF		X	
Véhicule tout électrique	- Groupes électrogènes - Piles à combustible - Stockage d'énergie mécanique - Supercondensateurs - Source d'alimentation pulsée	- électrocatalyseurs pour PEMFC, résistants aux polluants du champ de bataille		X	
		- SOFC capable d'utiliser des combustibles logistiques pour l'alimentation de systèmes tactiques		X	
		- générateur d'hydrogène compact à démarrage rapide et capable de fonctionner à basse température		X	
		- production d'hydrogène à partir de combustibles logistiques (Diesel/JP4)			X
		- système de démonstration d'alimentation pulsé pour un véhicule tout électrique	X		
Navire tout électrique	- Moteurs - Piles à combustible	- catalyseurs pour PEMFC, tolérants au CO	X		
		- SOFC capable d'utiliser des combustibles logistiques pour l'alimentation de systèmes tactiques		X	
		- production d'hydrogène à partir de combustibles logistiques (Diesel/JP4)			X
Micro-aéronefs et microrobots	- Batteries - Piles à combustible et piles à combustible microfabriquées - Générateur thermophotovoltaïque - Micromoteurs	- amélioration de la densité de puissance et des performances BT des piles à combustible directes au méthanol		X	
		- augmentation du rendement de la DMFC en réduisant la traversée du méthanol			X
Propulsion sans air de sous-marins et de submersibles	- Piles à combustible - Batteries - Alimentation nucléaire	- catalyseurs pour PEMFC, tolérants au CO	X		
		- stockage d'hydrogène à haute densité énergétique pour les exigences de système du soldat et de PSA			X
		- démonstrateur de PSA faisant appel au reformage de méthanol	X		
		- production d'hydrogène à partir de combustibles logistiques (Diesel/JP4)			X
Centrale d'énergie	- Hydroélectrique - Nucléaire - Magnétohydro-dynamique - Sources d'énergie renouvelables	- SOFC capable d'utiliser des combustibles logistiques pour l'alimentation de systèmes tactiques		X	
		- production d'hydrogène à partir de combustibles logistiques (Diesel/JP4)			X

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CHAPTER 1: INTRODUCTION

1 BACKGROUND

A wide range of electrical power sources are used in all aspects of the Canadian Forces (CF) operation and are currently deployed both in strategic and tactical roles. These power sources range from small "button cell" batteries such as those embedded in electronics to the large propulsion batteries installed on submarines, small diesel power generators for man-portable power to large diesel engine generators for naval vessels and deployable military camps.

It is obvious that there is no crystal ball available to precisely predict the future deployment of the CF. Notwithstanding political and social instabilities, the CF are preparing themselves for both the conventional, regional and anti-terrorist type warfare threats. The military will utilize both commercially and militarily produced tactical platforms and advanced electronics that will provide them with battlefield advantages and lower life cycle costs. However, military operations require a tremendous amount of energy, either as fuels to propel the weapon platforms or as electrical power to operate the tactical systems. Therefore one of the overarching requirements for the military is to have the necessary Advanced Power Sources (APS) to meet its energy needs while increasing tactical capability, lowering life cycle costs and reducing logistic burdens.

Military technology is evolving rapidly and introduction of new technologies into service will, in many cases, be dependent on suitable power sources being available. This is true, for example, of future soldier systems that are envisaged to include digital communication systems, GPS navigation, integrated helmet display, protective clothing and improved weapons that include laser range finding, IR sights etc. At the present time, existing power sources are incapable of meeting future military system requirements due to deficiencies in meeting energy density, weight, volume, signature, costs and environmental requirements. For this reason the CF [1] have recognized that advanced power sources is an underpinning technology critical to capability enhancement and pollution prevention.

The purpose of this study is to examine current trends in power source technology, to look at CF requirements out to the year 2020 and to define the Research and Development (R&D) opportunities that exist. The results of this analysis will assist the CF in formulating an appropriate science and technology strategy on the advanced power sources.

2 AIM OF THE STUDY

The aim of this study, entitled "Technology Trends, Threats, Requirements and Opportunities (T^3R&O) on Advanced Power Sources for the Canadian Forces in 2020", is to evaluate those power sources that have the capability of meeting future military requirements, to find the existing technology gaps and to identify research and development (R&D) opportunities. The results of this study are presented in this report.

3 ORGANIZATION OF REPORT

The report is organized in the following manner:

Chapter 1 - Introduction

Chapter 2 - Military Threats, Trends and Requirements

This chapter describes the battlespace technology trends that are expected in the future. This analysis was based on Department of National Defence (DND) [1] and Royal Military College (RMC) studies [2], NATO Research and Technology Organization (RTO) studies [3] as well as studies produced by the US and other Allies outlining future military concepts. Important trends in military technology that are expected to influence future CF operations include information assurance and total battlespace awareness, improved mobility, increased weapon lethality and widespread introduction of stealth technology. A set of power source requirements has been derived taking these trends into account. This selection is considered to be representative for the range of power source requirements that the CF will have in the future.

Chapter 3 - Power Source Technologies, Trends and Opportunities

This chapter presents the current state-of-the-art of the various power source technologies of interest, discusses future trends in the technologies and identifies research and development opportunities. To assist in the identification and evaluation on S&T opportunities, the procedure illustrated in Figure 1 has been used. In this procedure, for each specific requirement, all of the power sources are put through a series of "filters" to assess whether the power source has potential to meet the requirement and to select the most promising R&D opportunities. A brief description of these filters is as follows.

Filter # 1. Determine Power Source Options

For each generic military requirement, the range of power source options is examined to determine which of them has the potential to meet the requirement.

Filter # 2. Identification of Capability Gaps

This filter examines the power source options that have the potential to meet the requirement and determines if there are technology gaps in the technology that must be filled before the technology can be used. These technology gaps form the basis of the future R&D program. If it is clear that there is no technology gap then no further R&D is required to meet the requirement.

Filter # 3. Technical/Environmental/Health/Safety Issues

This filter examines the power source options that have passed through the first two filters to determine if some should be rejected on the basis of environmental, health and safety issues. The use of nuclear sources in the High Arctic might be considered environmentally unacceptable or the use of a hydrazine-fueled fuel cell might be rejected because of the toxicity of hydrazine. Other technical issues may also be considered here. Thermal signature is one possible example.

Filter # 4. Is There a Canadian Niche in the Technology Area?

This filter determines whether or not there are Canadian technologies that can be drawn on to make a significant contribution to the specific power source technology being examined. Expertise in Canadian industry, Canadian Universities and Governmental Institutes will be considered. As an example, the development of a small, portable fuel cell for Army field use might be considered favorably because of strong Canadian industrial and academic capabilities.

Filter # 5. Are R&D Being Done by Others?

This filter will examine whether R&D is already being done by others (in the commercial sector for example) or whether scarce defence R&D resources need to be committed if the problem is to be solved. In many cases, military power source requirements are more stringent than those of commercial power sources. Low temperature capability is an obvious example.

Filter # 6. Analysis on S&T Opportunities

This filter will analyze the results and make recommendations on S&T opportunities.

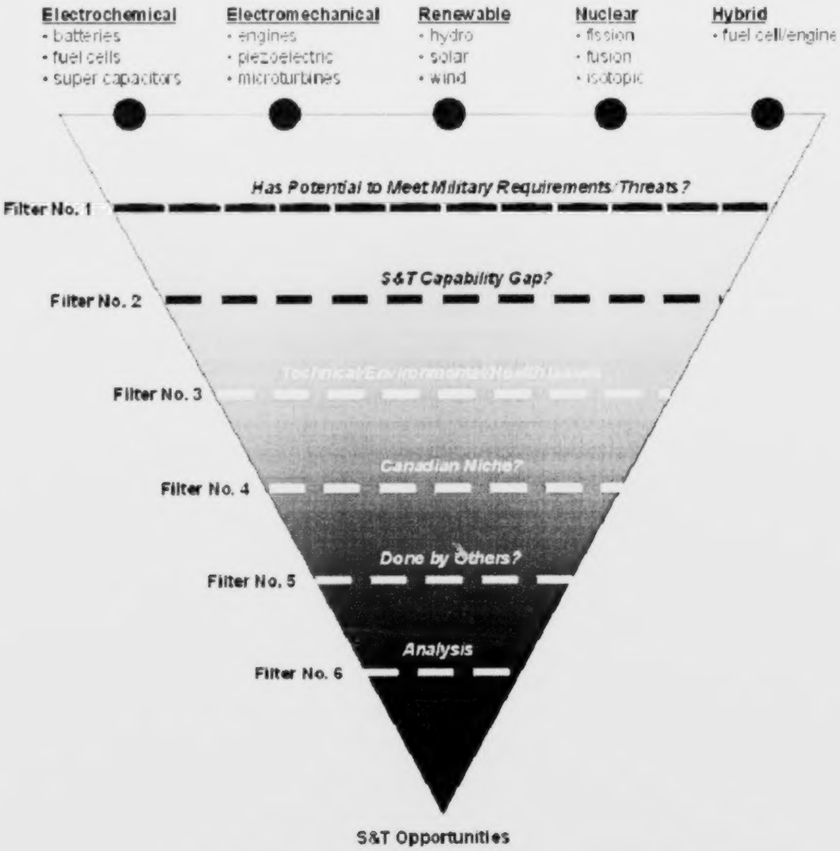

Electrochemical
• batteries
• fuel cells
• super capacitors
Electromechanical
• engines
• piezoelectric
• microturbines
Renewable
• hydro
• solar
• wind
Nuclear
• fission
• fusion
• isotopic
Hybrid
• fuel cell/engine
Has Potential to Meet Military Requirements/Threats?
Filter No. 1
S&T Capability Gap?
Filter No. 2
Technical/Environmental/Health Issues
Filter No. 3
Canadian Niche?
Filter No. 4
Done by Others?
Filter No. 5
Analysis
Filter No. 6
S&T Opportunities

Figure 1: Evaluation of Technologies and Identification of R&D Opportunities

Chapter 4: Analysis and Recommendations

This chapter will analyze the S&T opportunities identified in Chapter 3 and make recommendations on technology investment opportunities. It is almost certain that this list of opportunities will exceed the resources available. Thus a prioritized list of recommendations will be presented attempting to satisfy competing military requirements. Based on the T^3R&O analysis, a R&D program has been recommended by prioritizing a list of advanced power sources science and technology initiatives that DRDC and the Canadian Forces should consider.

CHAPTER 2: TECHNOLOGICAL THREATS AND CAPABILITY REQUIREMENTS

Military operations are evolving rapidly under the influence of Revolution in Military Affairs (RMA). RMA [1] is defined as a major change in the nature of warfare brought about by the innovative application of new technologies which, when combined with significant changes in military doctrine and operational and organizational concepts, fundamentally alters the character and conduct of military operations. It is imperative for the Canadian Forces to evolve with the RMA to take advantage of the leading edge and affordable technologies to enhance their capabilities. The development of a technology investment strategy to support future CF missions requires an understanding of the full range of operations that must be performed by the CF and the range of threats, including asymmetric threats such as biological and information warfare. A successful strategy must foster initiatives that develop new concepts and innovations. Military technology is the driving force behind the RMA and introduction of these new technologies into the battlefield will, in many cases, be dependent on the availability of suitable power sources to support CF operations and maintenance (O&M) requirements.

1 TECHNOLOGICAL THREATS

There are overarching threats that threaten future CF effectiveness resulting from the technological advances in the battlefield technologies. These are articulated under the NATO Land Operations in the Year 2020 [2] and Future Army Capabilities [3]. To achieve the Five Operational Functions: Command, Sense, Act, Shield, and Sustain, it will require technologies that can facilitate seamless integration of battlespace weapons, situation awareness and information systems, and geopolitical knowledge to assist the commanders in decision making. The backbone of these technologies are advanced electrical power sources. The five functions, individually or collectively, will rely on advanced power sources with a power range from microwatts to megawatts, and endurance of few microseconds for pulse power to months or years for deployed camps, central power and naval vessels as shown in Figure 2. The functionally integrated advanced power sources must also be capable of withstanding battlefield contaminants, and extreme climatic and operational environments. Failure due to inadequate power sources for critical sensors, weapons, computers, and the Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) [4] system platforms could jeopardize mission success.

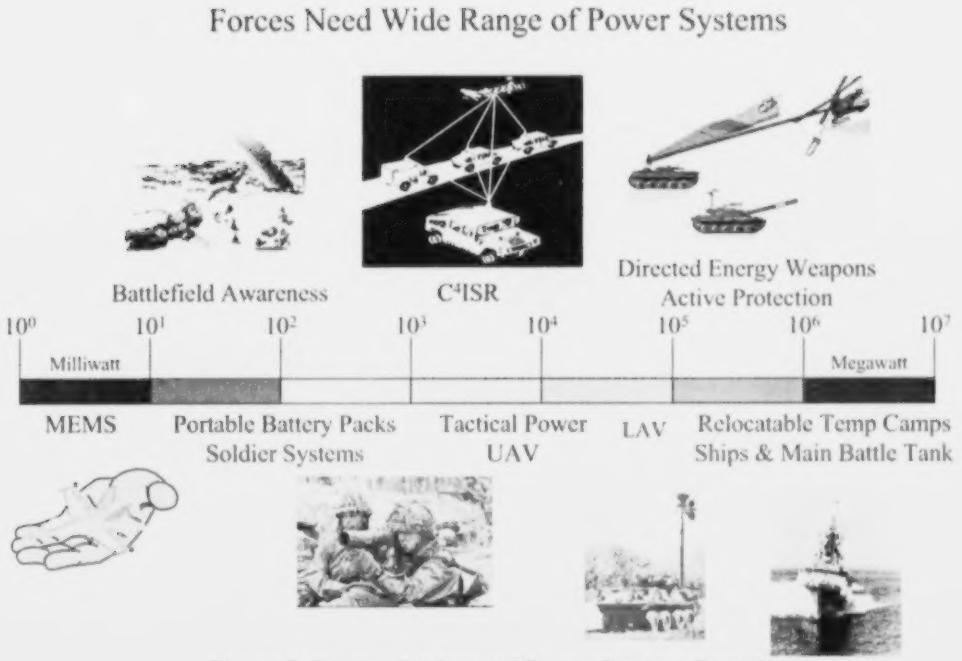

Forces Need Wide Range of Power Systems
Battlefield Awareness
C4ISR
Directed Energy Weapons
Active Protection
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Milliwatt
Megawatt
MEMS
Portable Battery Packs
Soldier Systems
Tactical Power
UAV
LAV
Relocatable Temp Camps
Ships & Main Battle Tank

Figure 2: Range of Advanced Power Sources Capacity

Notwithstanding the rapid technological advances achieved in the information management (IM), information technology (IT), electro-optic sensors (EO), weapons and mobile platforms, progress in advanced power sources has not kept pace with these system capabilities. Commercial grade power sources developed for the automotive and communication sectors typically lack the performance required for battlespace operation. One should recognize that advanced power sources for mission equipment have the same importance as the bullets for infantry rifles. The military has been extremely diligent in establishing standardization and quality control on bullets so that the soldier will have the correct caliber of ammunition for personnel safety, and to achieve range and firepower. Similarly, battlespace electronics and platforms demand the same level of diligence on advanced power sources, otherwise, fielding of deficient power sources could result in mission failure with deadly consequences.

As the CF become more dependent on battlespace technologies, there is a danger that there will be proliferation of military and commercial pattern power sources in the area of operational and logistic chain. As the CF is adopting the industrial best practice on supply chain management concept, the CF must also realize that industry often supplies substitutes to reduce logistic costs. However, what might appear to be a "form-fit-function" substitute might neither be technologically identical nor compatible with the military environment. Fielding of "unfit" power sources such as batteries, fuel cells, diesel generators, supercapacitors, energy and fuel storage devices could post significant risks to military operation. To reduce proliferation and fielding of "unfit" power sources, coordinated effort among the Equipment Management Teams (EMTs) and Project Management Offices (PMOs) will be required to adopt a level of power sources standardization, especially on batteries, fuel cells and portable hydrogen storage devices. To achieve a level of confidence on battlespace readiness, a Tri-Service team of life cycle materiel managers and technology experts will be required to manage and provide departmental guidance on advanced power sources. This team should be responsible for, but not limited to, the vetting and managing of research and development, technology insertion, technical evaluation, acquisition projects, and the fielding and in-service support on APS. This team should also provide guidance on the logistic supports and defence industrial preparedness such that "sustainment" issues are addressed systematically and cost effectively. Although this concept is contrary to the current Defence R&D Canada (DRDC) and the ADM (Mat) Equipment Program Management organizational structures, this concept is supported by the Defence Science Advisory Board articulated in their Report 99/2 - Advanced Energy Conversion: Implications to the Canadian Defence Capabilities" [5]. This holistic approach on the advanced power sources management is also complimentary to the ISTAR project implementation plan where technology insertion is an ongoing concern throughout the equipment acquisition and in-service phases.

In an endeavor to meet the CF demand for leading-edge battlespace technologies, DRDC has identified 17 technology drivers as shown in Figure 3, that are critical to the CF2020 initiative. Although " Power Sources" is identified as one of those technology drivers, it is currently not included in the DRDC list of the 21 R&D Activities. Since the Defence Program Guide and the Future Army Capabilities have not articulated any specific performance requirement on the future fleets, the T^{3}R&O study attempts to identify potential power source requirements against various generic military capabilities. This is not an exhaustive list of capabilities, but rather a representation of a broad spectrum of battlespace systems for that advanced power sources will be required to energize; and to identify critical science and technology investments that will be required to mitigate potential capability deficiencies (threats) resulting from technology gaps.

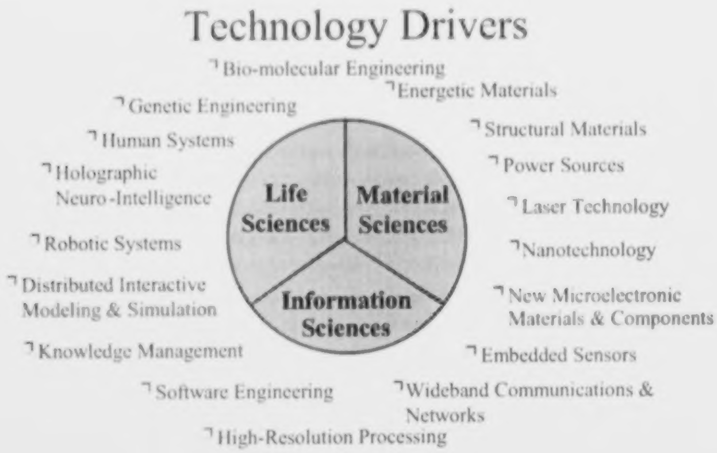
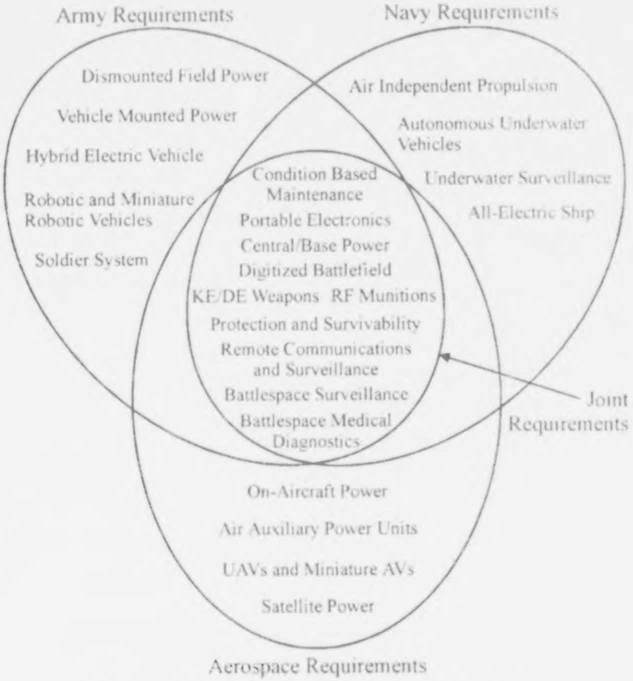

Technology Drivers
Bio-molecular Engineering
Energetic Materials
Genetic Engineering
Structural Materials
Human Systems
Power Sources
Holographic Neuro-Intelligence
Life Sciences
Material Sciences
Laser Technology
Robotic Systems
Nanotechnology
Distributed Interactive Modeling & Simulation
Information Sciences
New Microelectronic Materials & Components
Knowledge Management
Embedded Sensors
Software Engineering
Wideband Communications & Networks
High-Resolution Processing

Figure 3: Technology Drivers

2 ADVANCED POWER SOURCE REQUIREMENTS

To support the full spectrum of capabilities required for the COMMAND, SENSE, ACT, SHIELD and SUSTAIN operational functions, power sources with a power output ranging from microwatts to megawatts, with an endurance range from microseconds to months are required. In addition, sizes will range from that of integrated circuit chips up to 20ft ISO shipping containers. In order to facilitate analysis, power source requirements are presented by their application in current and future military equipment. Figure 4 shows that many requirements are joint requirements.



Army Requirements
Navy Requirements
Dismounted Field Power
Vehicle Mounted Power
Hybrid Electric Vehicle
Robotic and Miniature Robotic Vehicles
Soldier System
Air Independent Propulsion
Autonomous Underwater Vehicles
Underwater Surveillance
All-Electric Ship
Condition Based Maintenance
Portable Electronics
Central/Base Power
Digitized Battlefield
KE/DE Weapons RF Munitions
Protection and Survivability
Remote Communications and Surveillance
Battlespace Surveillance
Battlespace Medical Diagnostics
Joint Requirements
On-Aircraft Power
Air Auxiliary Power Units
UAVs and Miniature AVs
Satellite Power
Aerospace Requirements

Figure 4: Canadian Forces Requirements

The above mentioned requirements can be sorted by power range. Starting from the lowest to highest power consumption, the equipment is listed without any relations to priorities. For a better understanding, the characteristics of the different requirements which are the basis for the choice of a power source, are part of Table 1.

Table 1: Classification and Characteristics of CF Power Source Requirements

POWER RANGE	REQUIREMENTS	CHARACTERISTICS	APPLICATIONS
Micro Power (µW – 100 mW)	Sensors and Actuators	Microscopic scale High energy density/long endurance Environmentally friendly Energy harvesting desirable	Battlespace surveillance Condition based maintenance Battlespace medical diagnostics
Low Power (100 mW – 100 W)	Integrated Wearable Power	Extremely high energy density Highly efficient Low signature Safe and maintenance-free Low life cycle costs Energy harvesting desirable	Soldier System Pilot Survival Power Diver Support
	Portable Power	High energy density Compact/lightweight Low signature Non-polluting /low cost Long cycle life	Portable Electronics Protection and Survivability Underwater surveillance
	Miniature Robotics	High energy density Maintenance free Low signature Reliable	Miniature UAVs Miniature Robots
Medium Power (100 W – 100 kW)	Mounted/Mobile Power	Compact/lightweight Safe/easy-to-use Low fuel consumption Rugged/reliable Interoperability Continuous availability	Vehicle mounted power Dismounted field power Air auxiliary power
	Aerospace Power	High energy density Compact/lightweight Reliable/safe	On-aircraft power Satellite power
	Remote Power	Highly reliable Low fuel consumption Maintenance-free Energy harvesting desirable	Remote communications and surveillance
High Power (100 kW – 10 GW)	Vehicle Propulsion	High energy and power density Rugged/Safe Compact/lightweight Low fuel consumption Suitable for mil. environmental conditions Interoperability	Hybrid electric vehicle Submarine propulsion All-electric ship UAVs Torpedos Robotic vehicles
	Central Power	Low fuel consumption Low life-cycle costs Easy to use and to maintain Long MTBF, short MTTR Interoperability	Camp power
	Pulse Power	High energy and extremely High power density Compact Rugged	KE and DE weapons RF munitions

In an APS workshop held at NRC Montreal Campus in Ottawa in June 2001, the participants agreed that the following applications, which are a selection of the above mentioned future military equipment, represent the broad range of power requirements to be found in the CF. It is understood that there will be significant advances in reducing power consumption in electronics and sensors, however, it is arguable that these advances will not necessarily result in power and space reduction due to the pressure to add new capabilities and features. To facilitate the successful fielding of new technologies and the insertion of advanced technologies into current and future military equipment, collaboration will be required to define the power requirements more precisely so that the emerging military capability will not be constrained due to lack of suitable power sources.

2.1 Micro Power Systems

Micro Power Systems represent the power range from some microwatts to about 100 milliwatts. For applications at this power level, weight and size are critical aspects for power sources. As unattended and distributed deployment is desirable, a high energy density is needed for longtime operation.

2.1.1 Power for Distributed Sensors and Actuators

In the near future, MEMS sensors and actuators will see widespread use in both commercial and military systems. These new "intelligent microsystems" will interact with their environment by sensing, actuating and communicating without the need for external hardware. Some of the potential military applications for MEMS are listed below.

- Wireless Battlespace Sensors
- Condition-Based Maintenance Sensors
- Structural Health Monitoring Sensors
- Distributed Control of Aerodynamic and Hydrodynamic Systems
- Non-Invasive Biomedical Sensors for the Soldier

To optimize the usefulness of MEMS devices, micro power sources are needed that can be integrated with the other MEMS components. The general requirements for this power source are:

μW - mW power level
Capable of extended duration operation
Energy harvesting from the environment, such as solar, is desirable

2.2 Low Power Systems

Low power systems represent the power range from about 100 milliwatts to 100 watts. For applications at this power level, energy and power density of power sources are most critical in order to reduce the weight that has to be carried by the individual soldier. The low power systems have been subcategorized into integrated wearable power, portable power and power for miniature robotics.

2.2.1 Integrated Wearable Power Systems

Integrated wearable power systems can literally be worn by the military personnel as part of their suit or equipment. It serves to power all the devices a future soldier would need in the modern battlefield, for example the so called Soldier System.

The individual soldier will become the mobile platform to execute a combination of combat, surveillance and communication roles in the battlespace. It is envisaged that future soldier systems will contain a wide variety of advanced technologies including digital communications, GPS navigation, integrated helmet display, protective clothing, suit cooling and improved weapons. The desired power requirements recently defined by the US Army for this application are given in Table 2. The characteristics of the power source needed to meet these requirements are exceedingly demanding and are going to be very difficult or impossible to meet. At the present time, the best batteries have an energy density of about 350 Wh/kg. Diesel fuel has a theoretical energy density based on the lower heat of combustion of 13,200 Wh/kg. To achieve the target value of 5914 Wh/kg given in Table 2, a chemical to electrical energy conversion efficiency of 45% is required. This will be an exceedingly difficult target to meet.

Table 2: Land Warrior Power Source Requirements for 2020

	Goals
Mission Energy	1344 Wh
Mission Duration	336 h
Mission Weight	0.23 kg
Volume	1.1 dm^3
Volumetric Energy Density	1264 Wh/dm^3
Gravimetric Energy Density	5914 Wh/kg

In order to achieve this goal, in the US plans the average power consumption is limited to 18 W with a 40 W peak based on a lithium primary battery ($LiMnO_2$) or an equivalent power source. The US has defined the following targets in mission duration for a two pound battery: 12 hours in 2004, 24 hours in 2006, 48 hours in 2010, 72 hours in 2012 and 96 hours in 2014, which is a very aggressive timeline from a power source perspective.

2.2.2 Portable Power Systems

Portable Power Systems serve to power the electronic devices that a soldier needs to carry around. As the volume of equipment increases, also the need for highly sophisticated power sources does in order not to overload the soldier with them and their spares or recharging equipment.

Included in the category of portable electronic equipment are the wide range of portable radios, emergency locator beacons and personal locator beacons used by the CF. Batteries power these devices almost exclusively at the present time. Also night vision goggles, laser range finders and lightweight GPS receivers fall under this category. However, with the demand for increased endurance, range and power output at reduced weight, size and volume, batteries will not be capable of meeting these challenges. Table 3 gives an idea about the power consumption of current portable electronics.

Table 3: Example of Current Power Usage of Soldier Portable Equipment for a 3-day mission

	Name	Number of Units	Average Power	Intensity of Use: Day (<= 12 h)	Total Day Time Energy Draw	Intensity of Use: Night (<= 12h)	Total Night Time Energy Draw
			W	h/24h	Wh	h/24h	Wh
1	Night Vision Weapon Sight	7	0.069	0.0	0.0	2.0	2.9
2	Small Arms Laser Pointer	0	0.030	0.0	0.0	0.0	0.0
3	Laser Range Finder	7	0.080	0.0	0.0	2.0	3.36
4	Night Vision Goggles	7	0.050	0.0	0.0	6.0	6.3
5	Laser Rangefinding Binoculars	0		0.0		12.0	
6	Light Assault Radio (LAR)	7	0.045	12.0	11.34	12.0	11.34
7	Combat Net Radio (CNRP)	1	1.140	12.0	41.04	12.0	41.04
8	HF Radio	0		0.0	0.00	0.0	0.00
9	UHF Radio	1	4.000	2.0	24.00	0.0	0.00
10	Precision Lightweight GPS Receiver	7	0.500	2.0	21.00	2.0	21.00
11	Personal Flashlight	7	1.800	0.0	0.00	1.0	37.80
12	Night Vision Weapon Sight (Maxi-Kite)	1	0.069	0.0	0.00	1.0	0.21
13	Lightweight Laser Target Designator	1	265.00	0.5	397.50	0.5	397.50
14	LPL-30 Laser Pointer	1	0.360	2.0	2.16	0.0	0.00
15	SIMRAD Sniper Scope	0		0.0		0.0	
					497.04		521.45

The general requirements for these power sources are:

100 mW - 50 W
Light weight (high energy density)
Low cost
Good low temperature performance (-40 C)
High safety during normal use and abuse
Environmentally acceptable for disposal

2.2.3 Miniature Robotic Systems

The development of micro air vehicles and micro robots is expected to give the soldier on-demand information about his surroundings resulting in unprecedented situation awareness. The resulting capability will be especially useful in an urban environment. One of the principal challenges to be overcome is the provision of the necessary power. Small-scale power systems are needed that have very high energy and power densities. Systems with low acoustic and thermal signatures are desirable.

Typical power requirements are:

Power: 10 - 100 W
Silent operation
Liquid fuel operation desirable
Lightweight (> 1000 Wh/kg)
Low thermal signature

2.3 Medium Power Systems

Medium Power Systems cover the power range from about 100 watts up to about 100 kilowatts. For applications at this power level, efficiency, signatures and life cycle costs become more and more important. The medium power systems can be subcategorized into Mounted/Mobile Power, Aerospace Power and Remote Power.

2.3.1 Mounted/Mobile Power

The Canadian military has a strong requirement for tactical field power. Power is required for command posts, recharging batteries, O&M on equipment, field medicine, messing, water and heat production etc. As the cyberspace becomes an essential tactical and strategic area, advanced power sources will be required to execute various ISTAR, defensive and offensive functions, including electromagnetic spectrum denial and deception, battlefield networking infrastructure, sensors and Joint Task Force Headquarters, etc. At the present time, diesel engine generators are used for the higher power end (above 100 W), and batteries are used on the low power end. The requirement for tactical power with reduced acoustic, thermal and electromagnetic signature has existed for many years. With the improvement in electro-optic sensors, it will be more difficult to avoid detection. Emissions such as diesel engine exhaust, acoustic noise and thermal signatures can no longer be hidden, thus become an easily detectable target. Since in most missions critical operations are located near the power generators, the signature of the generator can easily lead to the targeting of installations. Since the Future Army Capability report articulates the requirement for seamless transition between strategic and tactical operations to meet rapidly changing political and military options, better power sources are required to meet these capabilities. Lacking advanced power sources in the battlespace could also render the CF non-interoperable with our Allies.

The general requirements for this application are:

0.1 - 100 kW power level
Silent operation
Liquid fuel operation desirable
Lightweight
Reduced thermal signature
Long life/low maintenance

2.3.2 Aerospace Power

Aerospace power includes the provision of electrical power to aircraft and spacecraft.

2.3.2.1 Aircraft Power

At the present time, the batteries used to provide power for starting aircraft are too heavy, lack sufficient capacity, are susceptible to heat and cold and can suffer from thermal runaway during use. The Griffin helicopter, for example, is limited to two start attempts before an auxiliary power unit must be used for starting. New aircraft power sources are needed that are lighter, have higher capacity, longer shelf life and improved crash worthiness. High energy and power density secondary batteries and fuel cells are possible replacements.

2.3.2.2 Satellite Power

Future military operations will depend increasingly on space assets for surveillance and communications. New concepts related to the deployment of inexpensive, mass produced and deployed satellites are emerging. Mass produced nano- and pico-satellites could be deployed in clusters of interactive satellites thereby improving survivability, reducing cost and increasing reliability. Provision of power for these small satellites will be of increasing concern.

2.3.3 Remote Power

Reliable sources of power will be required for a wide range of remote communications and surveillance applications where mission endurance is critical. This is an application that, at the present time, is largely met by using thermoelectric generators, or photovoltaic/battery/diesel generator hybrid systems. Improvements in power source signatures, capacity, endurance, efficiency and ability to use liquid fuels without compromising reliability are needed.

Typical requirements for these applications are as follows.

10 W - 10 kW power level
High reliability/low maintenance
Refueling once/year
Liquid fuel desirable
Unattended operation

2.4 High Power Systems

High Power Systems cover the power range from about 100 kilowatts up into the gigawatt range. For applications at this power level, requirements vary widely depending on the application. Therefore, high power systems can be subcategorized into propulsion power, central/fixed power and pulse power.

2.4.1 Propulsion Power

Propulsion power ranges from several hundred watts for the propulsion of hybrid electric vehicles over a few megawatts for submarines to some tens of megawatts for ships. Size, weight and efficiency play major roles for these applications.

2.4.1.1 Electric/Hybrid Electric Vehicles

Mobility, both to and on the battlefield, will be a key factor in future military operations. Fully electrically driven or engine-electric hybrid technology offers weapon platforms with increased maneuverability, survivability (active armor), firepower (advanced weapons), stealth (reduced signatures and increased deception), reduced weight and size (critical for autonomous vehicle), and improvements in system availability, integration flexibility, and cost effectiveness (Figure 5). When prime power for propulsion (mobility) is reduced, the electric platform can also power ISTAR systems, or electrolyze water to produce hydrogen for portable fuel cells to power for example soldier systems.

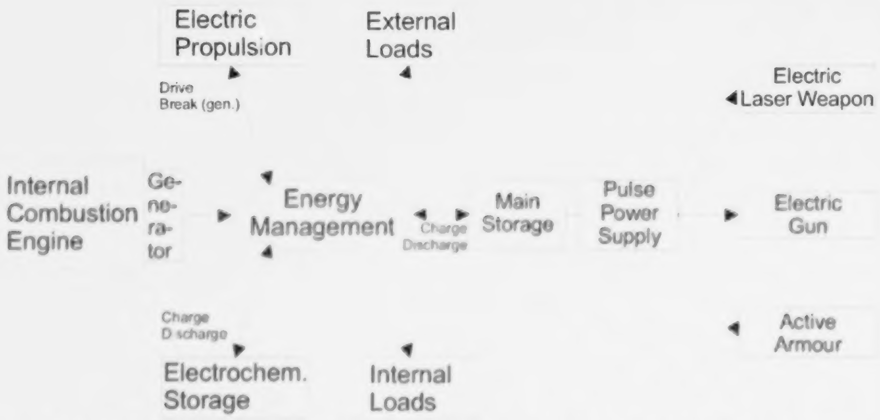

Electric Propulsion
External Loads
Electric Laser Weapon
Drive
Break (gen.)
Internal Combustion Engine
Ge-ne-ra-tor
Energy Management
Charge
Discharge
Main Storage
Pulse Power Supply
Electric Gun
Charge
Discharge
Active Armour
Electrochem. Storage
Internal Loads

Figure 5: Energy supply concept for a hybrid electric vehicle with electrical weapons

The technical papers prepared under the Land Force Technical Staff Program titled "Vetronics" and "Hybrid Electric Vehicles: Application in an Armored Fighting Vehicle" articulated the merits of the electric/hybrid electric vehicular platform. The power requirement is driven by the platform features and scope of the vetronics, and typically range from 5 kW to 300 kW for silent watch, mobility and electric weapons for a light armored vehicle, and up to 1 MW for a main battle tank. Fuel cells offer a higher efficiency than internal combustion engines over the wide power ranges and stealth capability. The enabling technologies include fuel cells, batteries, power conditioning and management, superconductors, high power motors and electronics, flywheels and super-capacitors, pulse power accumulators and conditioners, electric weapons and armors etc. The US Army has conducted advanced engineering prototyping on hybrid HMMWV and Bradley vehicles, and obtained impressive results on mobility and stealth operations.

2.4.1.2 Electric/Hybrid Electric Ship

A typical frigate requires a 25 MW gas turbine for tactical high-speed maneuvers, two 5-8 MW propulsion diesels for economical cruising, and four 0.7-1.0 MW diesel generators for ship services. Therefore a typical commissioned frigate would have 40-50 MW capacity and 7-8 prime movers, and a vast quantity of electric and hydraulic driven devices. In a hybrid electric ship, the prime movers would be used to generate electricity which then can be easily distributed through the electrical grid on the ship. This would still require a gas turbine for high-speed maneuvers, but for economical and silent cruising and ship services 3-4 additional prime movers (diesels or fuel cells) in the size of about 6 MW each would be sufficient (Figure 6).

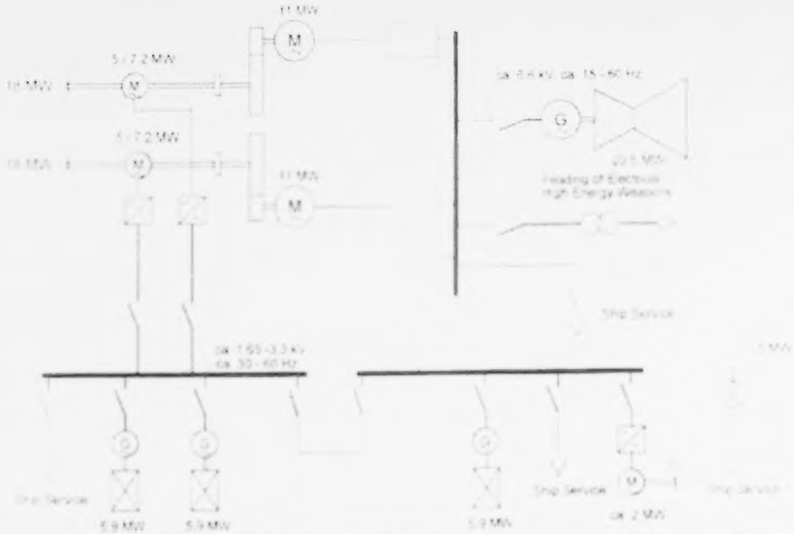


Figure 6: 4-Motor-Concept for an AES [by MTG Hamburg]

This reduces life cycle costs, but there are more advantages to a hybrid electric ship than that: increased survivability, reduced detectibility and feeding capacities for high power weapons. When compared to a land vehicle, the larger ship hull reduces size and weight constraints, but the larger power requirement and greater transmission distance pose a significant challenges to high power electronics, motors and the power bus. Superconductivity, high efficiency motors, electromagnetic shielding and device cooling are more demanding. The technologies needed for naval platforms, although similar in functionality to those for land vehicles, differ much in characteristics and performance parameters, such as shock and vibration, operating ambience, fuel type and maintainability, etc.

2.4.1.3 Air Independent Propulsion (AIP) of Submarines

Submarines have always been hybrid electric ships for several reasons, but first of all because it is impossible to use combustion engines under water for a longer period of time and in deep seas. Therefore, the diesel engines have been used to recharge a large capacity secondary lead acid battery, which provides the energy for submerged operation. For big submarines it was possible to integrate nuclear power plants to run the electric motor. When compared to diesel engines, fuel cell propulsion systems can provide submarines with important tactical advantages resulting from lower acoustic noise, lower structural vibration, and longer submersion duration. It can also improve the quality of life of the submariner by providing better quality air and a quieter environment. In the light of these advantages, under the Ferrostaal AG, IKL and HDW consortium, the German Navy engaged Siemens to develop an AIP prototype for the Type 205 Submarine, which was completed in 1995 [Janes Underwater Warfare Systems, 04 Aug 99]. The Canadian Navy has also identified a need for AIP capability for the VICTORIA Class submarines, thus CF has engaged Ballard Power Systems to conduct Proton Exchange Membrane (PEM) fuel cell development for AIP in the past years. Ballard has successfully developed the prototype and demonstrated the feasibility of this technology.

For future submarines the following requirements apply:

depending on the size of the vessel (Victoria Class: about 2400 tons displacement):
about 5 MW shaft power
Long submerged endurance
Low signature operation
Simple fuel logistic
Very high reliability
Shock proof
Safe and easy use and maintenance

2.4.2 Central/Fixed Power

Central/fixed power represents the power needed in CF bases and wings as well as needed in deployable camps. Although at the bases and wings the power is usually provided through the local hydro companies, backup power must also be considered.

Relatively large amounts of power are required for the operation of CF bases and large field installations. Typically this power is provided from grid power when it is available and from large Diesel generators at remote sites such as CFB Alert and deployable camps in the Balkans and Africa.

Typical power requirements are in the range from 100's of kilowatts to many megawatts.

a. Fixed infrastructures:

Examples:	RMC Kingston -	3 MW
	CFB Edmonton -	7 MW
	CFB Petawawa-	5 MW
	CFB Halifax -	14 MW

b. Deployable camps in Balkans:- 1 MW, with 1.5 MW capacity

2.4.3 Pulse Power

The requirement for pulse power is fairly new as the weapons that require it are yet under development. The energy needed for those shots is not that high, but has to be delivered in a timeframe from nano- to micro-, sometimes milliseconds. Thus the required power ranges from several tens of megawatts up to some gigawatts.

2.4.3.1 Pulse Power for Kinetic Energy (KE) and Radio Frequency (RF) Weapons

Weapons with increased lethality will be developed to counter improvements in armor and the use of electronic and optical systems. Technologies that will be developed include Kinetic Energy (KE) weapons and Directed Energy (DE) Weapons. KE weapons include electric (coil and rail) guns and electro-thermal chemical propellant guns capable of firing high velocity projectiles with increased lethality. DE weapons, such as high power microwave and laser/particle beams, will become increasingly important as a means of offensive/defensive denial and deception against the use of sophisticated electronic and computer systems on the battlefield. As a result, the requirement for compact power sources with high energy pulse capabilities will increase dramatically. In more detail, the general power requirements for some specific applications is are given in Table 4.

Table 4: Power Requirements for KE and RF Weapons

	EM Gun	**ETC Gun**	**ETC Igniter**	**HPM**
Energy/Pulse	40 MJ	4 MJ	0.4 MJ	40 kJ
Avg. Power	7 GW	1 GW	0.4 GW	4 GW
Peak Voltage	10 kV	16 kV	10 kV	1 kV- 1 MV
Peak Current	4 MA	150 kA	50 kA	-
Pulse Duration	6 ms	4 ms	1 ms	50 ns – 1 µs

2.4.3.2 RF Munitions

The development of a number of compact explosively driven RF munitions was disclosed by A.B. Prishchepenko in a paper that was delivered at the EUROEM Conference held in Bordeaux, France in 1994. In this paper, Prishchepenko described how these RF munitions might be used against a variety of military targets. These types of munitions are usually called non-nuclear electromagnetic pulse (NNEMP) devices. Their effect on electronic systems is similar to nuclear electromagnetic pulse (NEMP), but their range is much more localized. These munitions contain high power, broadband RF emitters launched over the enemy airspace to achieve close range high-energy destruction of EO sensors, battlefield networks and telecommunication systems. This reported development of RF munitions raised concern and interest in the US and other nations. Dr. Ira W. Merritt presented an assessment of the significance of these developments to the Joint Economic Committee of the US Congress 1998.

Typical power requirements for these munitions are as follows:

Energy/Pulse:	100 kJ
Pulse Power:	10 GW

CHAPTER 3: ADVANCED POWER SOURCES TECHNOLOGY, TRENDS, AND OPPORTUNITIES

1 BASICS

To choose the right energy source for an application, the characteristics of the source have to match as well as possible with the application's needs. The fundamental characteristics that define the source are described below. Given these numbers, one has to be careful about what the number includes; for example is it the energy density of a fuel itself or the whole fuel supply system, including the tank and the necessary auxiliaries. To make systems comparable, one should make sure that the numbers include the whole system.

1.1 Energy Density and Specific Energy

The energy density describes the amount of energy that can be stored per unit weight or volume. It is measured in Wh/kg or in Wh/m^3 or Wh/dm^3. One dm^3 is a liter. As energy is also measures in Joules, it could also be kJ/kg or kJ/m^3. One Wh is equivalent to 3.6 kJ.

Energy density = Wh/dm^3
Specific Energy = Wh/kg

1.2 Power Density and Specific Power

For many applications not only the energy density is a number of interest, but also the power density. This number describes how fast the stored energy can be withdrawn from the source, at what power level the energy can be released into the load. Power requirements range from milliwatts for sensor applications to watts and kilowatts for radio applications to megawatts for deployable camps and propulsion purposes. Electrical weapons like rail and coil guns or High Power Microwave and LASERs require power in the gigawatt range. Therefore another critical characteristic number is the power density. As power is energy per time: 1W = 1J/s, the power density is measured in W/kg or W/dm^3.

Power density = W/dm^3
Specific Power = W/kg

2 BATTERIES

Various types of primary (non-rechargeable) and secondary (rechargeable) batteries are pervasive throughout the Canadian Forces. These batteries contain several different chemical couples, that is the chemicals that form the positive and negative electrodes and react to produce the energy. Ideally, there could be one universal battery to satisfy all requirements, but such a battery will probably never exist or be affordable. This is because of the large range in power requirements and also the widely varying costs of the different couples. For example, one does not use an expensive, high energy density battery couple such as silver-zinc in a flashlight. Primary batteries, because they are only used once then discarded, will always have more capacity (ampere-hours of charge), have higher energy density, and will be much lower cost than their secondary equivalents. Secondary batteries cost more because they need to be built more ruggedly in order to last for many cycles. Secondary batteries also need to contain an excess of one of the electrode materials, or of electrolyte, in order to make recharging safe and to maximize battery life. In choosing between primary and secondary batteries, the cost of recharging also needs to be taken into account, as well as whether recharging is appropriate to the strategic application. Often, a secondary battery can be used for training purposes, whilst a primary one is used in the battlefield.

The designers of military equipment often do not consider the battery early in the process, which has frequently led to expensive, unique batteries for a particular piece of military equipment. Early consideration of the battery can lead to the adoption of standard cell sizes, for example, at reduced cost. This issue will not be discussed further in this document. Battery charging is an important aspect that will be discussed. The source of power for the charger needs to be considered in planning. At the base, electricity will come from the mains. In the field, it will come from a generator (vehicle or stand-alone diesel) or, in the future, a fuel cell or even from another battery.

Nickel cadmium batteries (NiCd) are possibly the closest that technology has come to a universal battery; small cells are used in portable radio batteries while large cells are used in batteries for vehicle starting. However, the small and large cells are very different in structure. The small cells are permanently sealed and only contain enough electrolyte to wet the electrodes and separator material, so there is no free liquid. The large cells are not sealed (they are called vented) and contain excess electrolyte (caustic alkali) that can spill out if the cells are inverted. These flooded cells are capable of providing more power per unit area of electrode material than the small sealed cells, because of the higher conductivity provided by the extra electrolyte. Obviously, one would not use a vented cell in a portable radio pack because it would spill. Vented nickel-cadmium batteries are used for vehicle starting (trucks and aircraft). They can provide more power than lead-acid batteries, especially at low temperatures, and their total life is much longer. However, they cost three times as much as lead-acid batteries and they require more maintenance than lead-acid batteries. Lead-acid batteries are known for their heavy weight, but it has proven difficult to surpass the low cost and ruggedness of lead-acid batteries. Indeed, the performance and reliability of these batteries is still being improved.

Another low cost battery couple in widespread military use is the common primary alkaline system (alkaline zinc-manganese dioxide). These batteries are mainly used in equipment such as flashlights. Their performance below −10°C is poor, but servicemen will keep them warm using body heat, if necessary. An alternative primary battery could be the lithium-sulphur dioxide system. These have a much better performance at low temperature, but they are not used as extensively because they are much more expensive and not as resistant to physical and electrical abuse as alkaline cells. In summary, the choice of battery for a particular application is not simple and cost is a very important factor. The demands on batteries are constantly increasing, whereby longer operating times are required from lighter-weight packs. Extensive research is underway internationally into advanced battery couples, such as lithium-ion and nickel-metal hydride. This research is mostly commercially driven so military requirements, such as low temperature performance down to –40°C, may not be considered. The following sections will briefly review established battery couples plus the new and experimental systems.

In the proceeding sections we will be using the following definitions:

Charge:

The charge contained in a battery, which determines its discharge time, is called its capacity and is expressed in ampere-hours (Ah).

Discharge Curve:

A discharge curve (or profile) is a plot of voltage vs. time: these may be almost flat or continuously falling (termed sloping). If a piece of equipment operates using constant wattage then, for a battery with a sloping discharge profile, the current being withdrawn is constantly increasing, which is very demanding. The energy obtained during a particular discharge falls as the power being withdrawn is increased, or if the temperature is lowered.

Pulse Power:

Pulse power is becoming increasingly important to the military. Pulsed performance for a particular battery usually needs to be determined in-house because the maximum possible power obtainable from a battery is usually only generated for a few milliseconds. Therefore, batteries need to be matched to the required pulse times. Pulse power in this article will be taken to mean that required for a fraction of a second for equipment such as an electronic gun, but also for the typical transmission times of a radio, to the order of several seconds.

2.1 State-of-the-Art

2.1.1 Primary Batteries

There are two main classes of primary battery in use in the CF. First there are portable batteries, which can be used in equipment in the battlefield, and can be further subdivided into aqueous primaries and lithium primaries. These may range from single cells (AA, C or D-size, for example) to 24V batteries for radios (such as the BA5590). Secondly, there are large format batteries, which include the thermal batteries that are used in various missiles, torpedoes and escape hatches. These are high power batteries that are usually only required to operate for a few minutes and can only be activated once.

2.1.1.1 Aqueous Portable Batteries

Portable batteries are likely to remain the power source of choice for low power missions of 24-48 hours duration because they are simple and cheap. Beyond that time, the weight of carrying additional batteries could be a problem. For training missions, rechargeable batteries are recommended, along with the means for recharging them. Table 5 (p. 43) summarizes the properties of selected primary batteries, which covers those in common usage and the newer advanced types, but excludes some of the older ones containing toxic metals, such as mercury, that are being replaced. The couples are listed in order of increasing open circuit voltage and, for couples with the same voltage, increasing energy density. The couples in the top half of the table are aqueous systems (except for Li/FeS_2), while the lithium types, with much higher voltage, are all non-aqueous (water decomposes above 2.0V). The higher voltages of the non-aqueous systems lead to higher energy densities and, often, higher power densities. However, the data can be somewhat misleading because the figures for the aqueous systems are for low-rate bobbin or button format cells, so their power is not maximized. It is not financially viable to make high-rate spirally wound versions of these couples (the spirally-wound electrodes are very long, so they have a high surface area, enabling high currents to be withdrawn from the cells). In contrast, all of the non-aqueous data are for the spirally wound design. It should be noted that energy densities are approximately the same for bobbin and spirally wound cells. The power densities listed in Table 5 are for a continuous current being drawn from a D-size cell, so the values for millisecond pulse power will be much higher. The individual couples are discussed below and the reader should refer to Table 5, as necessary.

a) Zinc-air (Zn/O_2)

Zinc-air batteries stand out in Table 5 for being high energy density for an aqueous electrolyte system. The reason that they are high energy density is that only the zinc electrode is stored in the cell. The oxygen is derived from the air and the cathode that reduces it is very lightweight. The most common format of this couple is the button cell for hearing aids and mobile communications. AA-size versions of this couple are a recent development and could be very cheap in mass production. The problems with these cells arise from the air electrode which, being permeable to oxygen, is also permeable to other gases and water. Depending upon the humidity, the cells can either dry out or the air electrode can become saturated with water. Carbon dioxide from the air will also react with the potassium hydroxide electrolyte to produce carbonate. Therefore, the cells need to be shielded from the air before activation. Large, prototype battery packs have been made for the US army using AA-size cells. These packs contain a small fan for circulating air around the cells when they are operating, then shutting off at open circuit. In this way, the cells can be reused after partial discharging. The US army is proposing to use these to recharge smaller batteries in the field. Other metal-air couples are possible, such as aqueous lithium-air, which would be even higher energy density but which would need to be discharged quickly in order to avoid excessive corrosion and could not be partially discharged. The lithium in these batteries is stabilized by mixing it with a hydrophobic polymer and by using a polymeric hydrogel electrolyte.

b) Zinc-manganese dioxide (Zn/MnO2)

Zinc-manganese dioxide cells using ammonium chloride or zinc chloride electrolytes are the old general-purpose dry cells. These have now largely been replaced by the newer alkaline version, which uses a steel can rather than a zinc can. The alkaline version is more expensive but it lasts longer, can generate more power, and does not leak. They also can be operated at –20°C and even down to –30°C at very low drain rates. The sloping discharge curve is not important for general-purpose use. These cells are cheap and reliable. This is a mature technology and the industry carries out its own research that leads to modest improvements, so this system will not be discussed further.

Mention should be made of rechargeable alkaline manganese cells (discussed in section 2.1.2.1 b)). These can be recharged 50 to 100 times and are very good for general consumer use. However, for military purposes, they do not compete with sealed nickel-cadmium cells, which have much better low temperature performance, higher power density and longer cycle life.

c) Silver-zinc (zinc/silver oxide, Zn/Ag_2O)

Silver-zinc cells have the highest volumetric energy density of any commercial aqueous system. They also have a long shelf life and good performance at –20°C. Coin cells find widespread use in small electronic devices such as digital watches: the flat discharge curve being important. The reason larger cells are not produced is simply because of the high cost of silver. This system will not be considered further, here.

d) Magnesium-alkaline (magnesium/manganese dioxide, Mg/MnO_2)

Magnesium-alkaline cells have a higher voltage than zinc-alkaline cells and are lighter weight because of the much lower atomic weight of magnesium i.e. 24 cf 65 for zinc. However, they are not in widespread use because, although they have a good storage life owing to a passivating layer protecting the magnesium, they suffer from excessive corrosion with intermittent discharging. The passivating layer also gives rise to a voltage delay. The US army is considering the use of these cells for training purposes; however, a better option would be to use rechargeable batteries. Therefore this system will not be considered further.

e) Zinc-iron (K_2FeO_4/Zn)

The discovery of this couple is very recent. It has an open circuit voltage of 1.75V and is being referred to as super-iron. The theoretical energy density of the iron electrode is higher than that of the MnO_2 of normal zinc-alkaline cells. The discharge product of the cell is essentially rust (FeOOH) and involves a change in oxidation state of the iron from 6+ to 3+. Iron is an ideal material to use for a battery because it is cheap, abundant and environmentally friendly. This couple could replace zinc-alkaline batteries in the future, but not enough details are known about its properties at this time. DND should keep a watching brief and carry out its own research.

2.1.1.2 Lithium Portable Batteries

Lithium is the lightest of all metals (atomic weight=7, atomic number=3) and yields the greatest charge per unit weight. However, lithium batteries have only been developed during the last 20 years. This was because lithium is very reactive: it dissolves rapidly in water, producing hydrogen, plus it reacts with oxygen and even nitrogen in the air. Fortunately, it was found that lithium is kinetically stable in certain non-aqueous electrolytes. In these cases, the lithium does, in fact, initially react but it produces an insoluble passivating film that protects the lithium from further reaction. Such films are electronically insulating but are conducting to lithium ions, enabling battery operation when the circuit is closed.

The battery couples to be discussed below belong to two types. The first are the liquid cathode systems and the second are solid cathode. With liquid cathode systems, it is a component of the electrolyte that is being reduced at the cathode, rather than the electrode itself. The liquid cathode systems are those with sulphur dioxide (SO_2, a gas that is dissolved in the electrolyte under pressure), thionyl chloride ($SOCl_2$, including a bromine-complexed version with BrCl), and sulphuryl chloride (SO_2Cl_2). The other lithium couples in Table 5 have solid cathodes. All the liquid cathode systems use a high surface area, polymer-bonded carbon electrode, supported on a metal mesh as the positive electrode. It is at this surface that the reduction reaction takes place, and the carbon is catalytic to the reaction. The insoluble, electronically insulating, discharge products precipitate onto the carbon surface and eventually passivate it. Therefore, cells are engineered to have the correct amount of carbon for complete discharging of the liquid cathode. For convenience, the carbon electrode is still usually referred to as the cathode.

The solid cathode materials are crystalline and the crystal structures have either tunnels or interlayer spaces that permit the transport of small ions such as Li^+ ions. These ions become strongly bound in the crystal lattice and the process is called intercalation. During the discharging of a lithium/manganese dioxide cell, lithium ions are intercalated in the oxide and the oxidation state of the manganese is reduced from the 4+ state to 3+. It follows that, with partial discharging of a cell the average oxidation state will be in between 4+ and 3+. The lattice needs to remain stable during intercalation because a major change in structure would prevent further intercalation. The rate at which a cell can be discharged depends on how quickly the lattice can accommodate the lithium, which depends upon the diffusion rate of the lithium ions in the lattice. This rate decreases exponentially with temperature (in degrees Kelvin) and is a problem at low temperatures, typically –20°C and below.

Comparing solid cathode and liquid cathode systems for low temperature operation, the liquid cathode systems should always support higher discharge rates because the reduction reaction occurs at the electrolyte/carbon interface and involves simple precipitation of the discharge product. With solid cathode systems, reduction at the surface is limited by the rate at which lithium ions, already intercalated, diffuse away from the surface into the bulk lattice. For high current operations at –40°C, a liquid cathode system is almost certainly necessary.

a) Lithium-sulphur dioxide (Li/SO_2)

Lithium-sulphur dioxide batteries are in widespread use in CF, in particular for night vision goggles, combat radios, hand-held chemical agent monitors, GPS, laser sight, and emergency beacons/radios. The cells have high energy and power densities and can operate down to –50°C. Being the first of the high-rate, spirally wound format lithium cells to be developed, there were some problems during development that caused cells to vent violently. These were engineering problems involving the use of the wrong cell hardware and the wrong ratio of lithium-to-sulphur dioxide (the present cells use a 1:1 molecular ratio,. These problems have since been rectified and the batteries have proven to be very reliable. When a problem does occur, it can usually be attributed to misuse or abuse. These batteries still need to be treated with respect, though, because the steel cell can contains a pressure of 3 to 4 atmospheres of sulphur dioxide. This pressure decreases with discharging. Some users are wary of a pressurized system and would prefer an alternative. Lithium-sulphur dioxide cells do occasionally vent in a non-hazardous fashion. The sulphur dioxide fumes are toxic in an enclosed space, although their strong odor alerts the user to the problem. Actual battery packs have several safety devices to prevent abuse: blocking diodes to prevent charging, electrical fuses and thermal fuses. This battery couple is the safest of the liquid cathode systems and, as discussed above, a liquid cathode system is needed for operation at –40°C. When a current is initially drawn from these batteries at low temperature, the voltage can drop appreciably for tens of seconds. This is because it takes time to break down the passivating layer (of lithium dithionite) on the lithium electrode. The problem is referred to as voltage delay. Voltage delay tends to increase with storage and is minimized by ensuring that the cell components are as dry as possible before assembly.

The Li/SO_2 battery industry is mature and it is not expected that any major advances could be made with this system. Some present work in the USA is aimed at drawing more current from individual cells by the use of extra current collecting tabs along the electrodes. This work is being carried out because the alternative lithium-thionyl chloride system, which can generate more power, is much more expensive. Possible further uses for this technology are in sonobuoys, climate sensors and unmanned vehicles. In the USA, CECOM is cutting back on Li/SO_2 procurement and is testing lithium-manganese dioxide batteries in their place. With less US demand, Li/SO_2 batteries could become very expensive. There are presently three manufacturers in North America: SAFT, GA; Eternacell, NJ (previously Power Conversion Inc.); and Eagle-Picher Energy Products Corp. (EPC) in Vancouver, B.C. (previously BlueStar Battery Systems and Ballard Battery Systems). Production could become consolidated in Canada because of the –40°C operational requirement, which is not expected to be relaxed because of opening up of the Arctic to navigation.

The main area of research concerning Li/SO_2 would be aimed at replacing it with an unpressurized system. For very low temperature operation, the alternative liquid cathode systems are not as safe or reliable in the spirally wound format. In addition, the pressure inside these systems actually increases with discharging, because sulphur dioxide is a product of the reaction. One possibility for the future is to use a solid cathode system for temperatures down to –20°C, but to keep a stock of lithium-sulphur dioxide batteries for operations below that temperature, since these batteries have a shelf life of up to 10 years. As regards emergency beacons, these should remain using lithium-sulphur dioxide batteries, especially for aircraft. The other liquid cathode systems will be discussed in the proceeding sections.

b) Lithium-thionyl chloride (Li/$SOCl_2$)

Spirally wound lithium-thionyl chloride batteries are higher voltage, higher energy density and fundamentally higher power than their lithium-sulphur dioxide counterparts. Low-rate bobbin design cells are commonly in use for memory back up for computers and for outdoor remote monitoring applications. Bobbin cells are firmly established in the market. However, the data in Table 5 are for high-rate, spirally wound cells. These are produced in limited quantities for specialized military or commercial applications. There are several potential problems with these cells when it comes to routine use of them for applications such as portable electronics. Because the cells are high-power, they are correspondingly more violent when subjected severe abuse such as nail penetration. Here, the nail (or bullet) can get red hot and poisonous hydrogen chloride fumes are emitted, followed by the lithium catching fire. The electrolyte in these cells reacts with water, including moisture in the air, to produce hydrochloric acid. This readily dissolves many metals and would destroy electronic equipment. Another problem with the high rate cells has been storage life. Although the lithium is protected by a passivating film (of lithium chloride), this film does continue to grow appreciably with storage (unlike for lithium-sulphur dioxide cells), such that voltage delay can be severe at reduced temperatures. This problem has been addressed by coating the lithium with a polymer. Although this is effective for unused cells, the coating is destroyed upon initial cell use, so the cell cannot then be partly used then stored. Further research could be undertaken into this system; however, it is not likely to be safer than lithium-sulphur dioxide for general use and it is more expensive. Limited quantities may be used by DND for weapons, including pulse power for lightweight electronic guns, but it is not considered that DND should initiate a research program. The main supplier at this time appears to be SAFT of France. DND should keep a watching brief on development.

Another form of this system is the so-called bromine complexed one. This has a limited amount of bromine chloride added to the electrolyte, which gives the cell a higher voltage. However, this complex is consumed first during discharging and the cell voltage then reverts to that of normal lithium-thionyl chloride. From this point of view, these cells only appear to be useful if the user wants 3.7V to 3.8V from a single cell at low temperatures.

c) Lithium-sulphuryl chloride (Li/SO_2Cl_2)

Sulphuryl chloride is a corrosive liquid similar to thionyl chloride, that reacts with water to produce both hydrochloric and sulphuric acids. The discharge reaction of this couple produces lithium chloride and sulphur dioxide, so the pressure inside the cell increases with discharging. The high voltage of this couple during initial discharging can be attributed to disproportionation of the sulphuryl chloride to sulphur dioxide and chlorine, with the high voltage arising from the chlorine. Again, this is considered to be a potentially hazardous system for routine use and interest in it has declined in recent years. Consequently, no active research by DND is envisaged.

d) Lithium-carbon monofluoride (Li/CF_x)

Lithium-carbon monofluoride is a solid cathode system, is higher energy density than lithium-sulphur dioxide, but is lower power. During the development of lithium-sulphur dioxide batteries there were problems with the development of a Personal Locator Beacon (PLB) battery for the CF and lithium-carbon monofluoride batteries were used as an interim measure. Tragically, a CF Hercules crashed near Alert during that time in cold weather and the PLB batteries yielded very little operational time because of the very cold weather, inhibiting rescue.

Lithium-carbon monofluoride is a safe couple, with good performance down to –20 °C. The carbon monofluoride itself is made in Japan, but future supplies are uncertain. The USA may start to produce it. The system may have room for improvement by developing an electrolyte with better conductivity at low temperatures. DND should keep a watching brief on this technology.

e) Lithium-vanadium oxide (Li/V_2O_5)

Lithium-vanadium oxide batteries are another relatively low rate and safe system that has a high energy density. One reason why these have not seen widespread use is that discharging occurs at two distinct voltages, whereby the first third of discharging occurs at 3.3V, then the rest at 2.4V. Such a large difference means that the system is impractical for many applications, so no research is planned.

f) Lithium-manganese dioxide (Li/MnO_2)

Lithium manganese dioxide cells are fairly common in small format button cells. High-rate D-size cells are a recent development for this couple. They have a higher energy density than lithium-sulphur dioxide but a lower power density. Their performance also falls off rapidly below –20°C. A problem with these cells is that the contents are highly inflammable and they burn with a very hot flame. Several incidents have been reported at manufacturing plants and military research bases, including buildings being destroyed by fire. The electrolyte in these cells contains inflammable ethers and lithium perchlorate, which is an oxidant. In addition to that, manganese dioxide is an oxidizing catalyst. Under abusive testing conditions, cells have been described as burning like a Roman candle. The cells are less likely to vent violently than lithium-sulphur dioxide but, when they do, they are more likely to cause a fire. The cells catch fire on bullet penetration. BlueStar Battery Systems of Vancouver (now Eagle-Picher) tried to develop cells with less inflammable electrolytes but, unfortunately, these were found to have a very poor storage life and the work was abandoned.

Very recently, the US army has sponsored the development of pouch cells (with Eagle-Picher/BlueStar and Ultralife). Here, the electrodes are large and rectangular and are stacked together. The cell container is a sealed, metallized plastic pouch. Use of plastic packaging leads to a 25% increase in energy density over a steel can. At first thought, these cells may not sound very safe, but they have passed safety and abuse testing in the USA and they are safer than the D-size steel can version. When the pouches get hot from an abusive condition, the plastic pouch will begin to leak electrolyte before it reaches the flash point, and the battery may shut down before anything hazardous occurs. The electrolyte in this case is not acidic or noxious and the solvent can quickly evaporate without incident. These cells still do not match the low temperature performance of lithium-sulphur dioxide, but DND could pursue the development of this kind of primary battery for use at –20°C and above. For certain applications, such as communications radios, a supercapacitor placed in parallel with the battery may allow operation at temperatures below –20°C. This is another area that DND could pursue. Supercapacitors are a new technology that will be discussed in a later section. The US army CECOM is planning to have the soldier "wear" these batteries in pockets in a flack jacket. In this case, low temperature will not be an issue. If these pouch cells replace most of the Li/SO_2 batteries in the US military, this could lead to an increase in the unit cost of Li/SO_2 batteries for the CF. Therefore, DND will need to keep an eye on developments.

g) Lithium-iron disulphide (Li/FeS_2)

This couple is different from the other lithium couples listed in Table 5 in that the operating voltage is only 1.5V. Nevertheless, the energy density and power density are high and the voltage makes these cells ideal for replacing alkaline cells when higher rates or low temperature operation are required. The low temperature operating limit is also lower than that of lithium-manganese dioxide. At the present time AA-size cells are available from Eveready Inc. and are marketed for commercial use in cameras. DND could investigate the use of this couple in C- and D-size cells for general use in place of alkaline cells for high rate and low temperature applications. This work would entail an initial in-house study of commercial cells and the contracting of the assembly of prototype C- and D-size cells for evaluation.

2.1.1.3 Large Format Primary Batteries

a) Thermal Batteries

Thermal batteries are a type of reserve battery, which means that they need to be activated before they will work. In this case, activation involves melting the electrolyte in order to make it conducting, which is achieved using a fuse. Because the electrolyte is solid at room temperature, the shelf life of these batteries is very long. The operating temperature of the batteries is of the order of 350°C. Thermal batteries are usually used in missiles, torpedoes, navy mines, guided artillery, countermeasure systems, and aircraft ejection seats. Given the specialized, limited application of thermal batteries, it is not envisaged that DND will carry out research in this area, but rather should keep a watching brief on work carried out in NATO countries. The main manufacturer of thermal batteries in North America is Eagle-Picher in Missouri.

b) Lithium-thionyl chloride

Large format versions of lithium-thionyl chloride cells have previously been used for standby power in missile silos, but these are now being taken out of service. The US Navy is currently developing large cells for use in UUVs. Again, there is no reason for DND to carry out research and development on these systems.

2.1.2 Secondary Batteries

For the purposes of this discussion, secondary batteries will be split up into three types. These are aqueous and lithium portable batteries (the rechargeable versions of those in the previous section on primary batteries) and large format batteries. The latter will include starter batteries and submarine batteries as well as stationary back-up power sources.

2.1.2.1 Aqueous Portable Secondary Batteries

Table 6 (p. 44) lists selected portable secondary batteries in order of increasing open circuit voltage and, where this is the same, increasing energy density. The last two couples are non-aqueous and the voltage can be seen to be 2 to 3 times that of the aqueous couples. Although the energy density of lithium-ion is 3 times that of lead acid, it will be seen that the pulse power density of lead acid exceeds that of lithium-ion. This is because of the higher resistance of the non-aqueous electrolyte in the lithium-ion systems and the slow rate of diffusion of the lithium ions into the host electrode material. The number of cycles expected from the different couples is also included. Manufacturers often give misleading figures for this, because the number of cycles obtained depends on the rate at which the cell is both charged and discharged and also on how deep the discharge is. A 100% discharge is a discharge to whatever the end-voltage is defined to be (or, as is sometimes the case, not defined), and is not to 0.0V. Cycle life will also depend upon the cell temperature and how much the battery is subjected to shock and vibration, during which active material may be lost from the electrodes. For example, with lead acid car batteries, the plates shed material, which eventually builds up at the bottom of the battery case and short circuits the plates (it should be added, though, that lead-acid car batteries are particularly rugged). The reader should make frequent reference to Table 6 as the different systems are outlined below.

a) Nickel-cadmium (Cd/NiOOH or NiCd)

Nickel-cadmium batteries have been around for over 100 years and have progressively been improved upon. The portable cells are a sealed version of this couple. These contain a larger capacity Cd electrode than the Ni electrode so that the Ni electrode becomes fully charged first and produces oxygen. Meanwhile, the cadmium electrode is still being charged so it does not produce hydrogen. With overcharging, the oxygen that is given off at the Ni electrode is able to chemically react with metallic Cd to produce cadmium hydroxide. In this way, the unwanted oxygen gas is removed, preventing a build-up of pressure. Because the Cd electrode is never fully charged, no hydrogen is evolved from that electrode: this being a gas that cannot be recombined in the cell. In order to facilitate oxygen gas recombination, the cell is not flooded with electrolyte (it is described as starved electrolyte), enabling the oxygen to diffuse more rapidly from the Ni electrode to the Cd electrode. Because of the starved electrolyte, these cells cannot support such high current densities as flooded cells do.

Batteries containing NiCd cells are in widespread use in the CF and are a major power source in the TCCCS program. The batteries give very good performance at low temperatures. In radio operation, the batteries can yield 90% of their room temperature capacity at –20°C and 65% at –30°C. However, there are environmental concerns about portable NiCd batteries because of people throwing them away with their rubbish instead of recycling them (cadmium is a toxic heavy metal), which may lead to a ban on their production in the future. The portable batteries in CF use do contain commercial cells, so it is not certain what will happen. DND should assume the worst and be prepared to change to another system, such as nickel-metal hydride or lithium-ion. At the present time, these two systems can compete with NiCd at –20°C, but are worse at –30°C. The portable NiCd system is a mature technology that has seen steady improvement over the years (such as elimination of the memory effect by using polymer-bonded cadmium electrodes). Because of the environmental problems mentioned above, no further research need be carried out by DND. There are no Canadian manufacturers of nickel-based batteries but INCO, in Mississauga, carries out research into nickel oxide electrodes for all of the nickel based couples.

b) Rechargeable alkaline manganese dioxide (RAM, Zn/MnO_2)

Primary alkaline manganese dioxide cells were discussed earlier. The rechargeable version is a recent development. The cell chemistry is the same except the zinc electrode is much lower capacity than the manganese dioxide one, so that the manganese ions only get discharged from the 4+ valence state down to 3+, rather than to 2+, as happens when completely discharging a primary cell. The manganese can be recharged from the 3+ state compound, but not from the 2+ state compound. These cells are cheaper than NiCd, but they are poorly performing below –10°C. They also have a limited cycle life of 50 to 100 cycles. This means that they are good for consumer applications, but not for military outdoor use. The manufacture of RAM cells is licensed to several companies around the world by Battery Technologies Inc., of Toronto. BTI carries out its own research aimed at improving the cycle life of RAM cells. The US Army is presently sponsoring work, at Rayovac, to develop a spirally wound D-size cell.

c) Nickel-metal hydride (metal hydride/NiOOH or NiMH)

Nickel-hydrogen batteries are used in space vehicles. They use hydrogen gas contained in a pressure vessel and they will not be discussed here. The much lower cost, terrestrial version is nickel-metal hydride. Many metals absorb hydrogen, which is present in the metal as hydrogen ions, just as lithium metal is intercalated as an ion For battery applications, the metal needs to be lightweight and the hydrogen readily available. In practice, alloys are used, such as $LaNi_5$. The cells are very similar to NiCd, with the same operating voltage and electrolyte. NiMH cells can have 50% more capacity than NiCd, but they are also correspondingly more expensive. NiMH has drawbacks of a fairly high self-discharge rate, arising mainly from the metal hydride electrode, and a lower maximum discharge rate than NiCd. The US army is currently replacing several of its NiCd batteries with the NiMH equivalent. This couple is in competition with lithium-ion for use in portable electronic devices such as laptop computers. Lithium-ion cells cannot support such high currents, but they have three times the voltage and it is wattage that is the important factor. The TCCCS program has recently purchased a ruggedized NiCd charger for use in the field. It should be relatively easy to upgrade these chargers to NiMH batteries, but it may not be possible to convert them for use with lithium-ion. Problems such as this should be borne in mind for future acquisitions of batteries. In view of the commitment by TCCCS to a NiCd charger-analyzer, it is suggested that DND carry out research aimed at improving the low temperature performance and reducing the self-discharge rate of the nickel-metal hydride system.

d) Lead-acid (Pb/PbO_2 or Pb-acid)

Lead-acid is a very old system, although small portable cells are a recent development. The lead-acid couple has a very high voltage for an aqueous system of 2.0V. Bolder Batteries, Colorado, has recently introduced a very high rate 9/5 C-size cylindrical cell that, when used in a 12V battery, is capable of starting a small engine. These batteries are being marketed as a reserve power supply for emergency recharging of an automobile starter battery, although they are not identified as lead-acid in the advertisements. The cells are designed for high currents and do not have a very high capacity. However, the batteries have a very high power density and could be used in lightweight electronic guns. DND could investigate possible pulse power applications of the cells. No fundamental materials research is envisaged, but DND could look into possible ways of extending the cycle life of these batteries.

2.1.2.2 Portable Lithium Secondary Batteries

Following the development of lithium primary batteries, it was natural to try and develop rechargeable versions. Attempts were made at developing several couples, such as Li/TiS_2, Li/SO_2 and Li/MoS_2. These cycled efficiently but cells tended to vent or explode after many, or even only a few, cycles. The problem was usually attributable to the lithium, which tends to grow long whiskers (called dendrites) upon deposition during recharging. These can eventually penetrate the separator and short-circuit the cell. Molten lithium is highly reactive so an explosion often resulted. The batteries could, in fact, be made to behave well in a laboratory environment, but use by the general public is another matter. This was the downfall of Moli energy of Vancouver, B.C., who was the first company to market lithium metal rechargeable batteries. These used Li/MoO_2 cells in batteries for cellular phones. One user had a cell explode close to his face and the batteries had to be withdrawn from the market. This user had left the battery on charge most of the time without using it much. Since that time, development has shifted to lithium-ion cells. These have been on the market since around 1991, being first introduced by Sony of Japan, although much of the basic research came from western countries.

a) Lithium-ion cells (Li-ion)

Most commercially produced lithium-ion cells use lithium cobalt dioxide ($LiCoO_2$) for the positive electrode and carbon, usually in the form of graphite, as the negative electrode. Both of these are stable in air and, when assembled, produce a cell in the discharged state. The electrolytes have to be non-aqueous because of the high voltage obtained in the charged state, 4.2V. With cell charging, not all of the Li can be removed from the oxide, otherwise the structure would change and the oxide would no longer be rechargeable. Cells need to be kept within a certain voltage window, otherwise capacity can be partially or completely lost. In the case of prolonged overcharging, cells can also go into thermal runaway. With overdischarging, the copper current collector of the negative electrode corrodes and eventually causes a short circuit. Because of these problems, lithium-ion batteries need dedicated electronics in order to keep the cell voltages within their safe window. With modern electronics, this is not very expensive or bulky, although it does increase the price. Cobalt metal is also expensive so these batteries tend to be used in luxury portable goods, such as computers and video cameras.

Lithium-ion cells have a much higher energy density than portable NiCd cells do, plus a higher pulse power density. On the other hand, the cost is also appreciably higher and the cycle life is lower. In fact, the capacity tends to progressively decrease from new and cannot be recovered. This contrasts with NiCd, which can be reconditioned close to the original capacity. Because of this degradation of capacity, lithium-ion batteries are not necessarily always the best choice, depending on the life expected from the piece of equipment involved. In the commercial world, the electronic equipment might become obsolete before the battery reaches its end of life, whereas the military application is more long term. Being non-aqueous, the performance of Li-ion falls badly at low temperatures. Most commercial cells are very poor below –20°C. The US army is developing an electrolyte for operation down to –30°C, which is also an area that DND could pursue. Apparently, the passivating film on the anode is the major contributor to the resistance of the cell, particularly at low temperatures, so this is an area in need of investigation. The resistance of the film will be determined by the components of the electrolyte, so the effect of additives to the electrolyte should be investigated.

The US Army has recently carried out research that has led to increased discharge rates by using a two-phase lithium cobalt oxide / silicon dioxide or titanium dioxide structure, where the latter compounds provided greater accessibility of the electrolyte inside the electrode. Research along similar lines could be carried out by DND and also applied to the lithium-ion polymer system. Commercial and university based research groups are actively pursuing the development of low cost and longer cycle life alternatives to $LiCoO_2$. In Canada, the NRC battery group is active with partial funding from DND, looking for manganese based oxides that are stabilized by doping with other metals. At Dalhousie University, Halifax, Dahn's group is investigating alternatives to carbon that have a higher capacity for lithium intercalation. Because of the high level of research in this area, DND should keep a close watch on developments.

b) Lithium-polymer and lithium-ion polymer (Li-ion polymer or LIP)

It was previously believed that lithium rechargeable cells with a solid polymer electrolyte would not be subject to short-circuiting via lithium dendrites, like the liquid electrolyte couples were. Unfortunately, this is not the case and it is not clear whether such cells can be made to be safe. DND has already sponsored work carried out at Hydro-Quebec, whose efforts were later financed by the US Advanced Battery Consortium, for EV application. DND should keep a watching brief on this technology.

As with primary batteries, pouch cells are possible with some of the rechargeable systems. For lithium-ion, the development is called lithium-ion polymer. This embodiment allows cells to be made in any shape and size. Some forms of this are also flexible because they are composed solely of laminated doped polymers. A company in Toronto (Electrofuel Inc.) is presently leading the market with cells designed for laptop computers. These use graphite and lithium cobalt oxide electrodes and the electrolyte is held in a spongy form of a polymer. The cells are not high rate, but they are the highest energy density of any rechargeable system on the market. These cells can already meet the requirements of communications equipment at room temperature, but the capacity falls more rapidly with temperature than that of NiCd, and they have little capacity below –20°C. As with the primary systems, these lithium-ion pouch cells are safer to certain abusive conditions than the normal steel can versions: in this case they are less hazardous to gross overcharging, because the plastic pouch opens up at relatively low temperatures and the solvent can evaporate without catching fire.

Lithium-ion polymer cells are likely to be an important system in the future. DND could carry out research into improving the high rate and low temperature performance, which could also include a hybrid system with a supercapacitor (the latter will be discussed in a following section). Research into lithium-ion polymer cells should be carried out in collaboration with Electrofuel Inc. of Toronto.

2.1.2.3 Other systems

DND arguably does not have the resources to carry out research aimed at discovering new battery couples, rather, it should keep a watching brief on novel systems and then decide whether a particular system reported by others is worthwhile trying to develop for outdoor use in Canada. There are many other battery couples that will not be discussed here, especially other lithium systems, such as lithium-sulphur. Some of these use lithium metal electrodes and make use of separator material that shuts down the flow of ions if the cell temperature gets too high. Such lithium metal systems will have higher energy densities than lithium-ion because the graphite in the latter cells is simply a host to the lithium, so constitutes extra weight and volume. Whatever the outcome from the present document concerning a choice of battery couple to pursue, DND needs to be prepared to switch resources to alternative promising systems whenever they might appear.

2.1.3 Large batteries

Here, large batteries will encompass vehicle starter, lights and ignition (SLI), reserve power, and traction batteries. These are in widespread use in land vehicles, aircraft and submarines. As regards research, state-of-charge and state-of-health are issues for most of these couples (including the portable versions) that DND can pursue using novel techniques. Table 7 (p. 45) summarizes the various battery couples but, for brevity, not all of the possible couples have been included. For example, zinc-bromine has been omitted because it uses a flowing electrolyte and is therefore complex and not rugged for field use. Most of the systems discussed are for power storage, but mechanically rechargeable aluminium-air and zinc-air are for power generation.

a) Nickel-cadmium (Cd/NiOOH or NiCd)

As already mentioned, nickel-cadmium batteries have a much better cycle life than lead-acid, but they cost 3 times as much. Most large format batteries are flooded electrolyte. The highest rate versions have cadmium electrodes supported on a high surface area sintered nickel substrate and suffer from the memory effect, which can be removed by a slow, deep discharge. Sealed batteries are now appearing for aircraft use. Many electric vehicles use nickel-cadmium batteries. This is again a mature industry and DND does not need to carry out basic research on this couple.

b) Nickel-metal hydride (metal hydride/NiOOH or NiMH)

Large format nickel-metal hydride cells are being developed for use in electric vehicles. As for the portable versions, these are higher energy density than NiCd, but are more expensive and have lower power, especially at low temperatures.

c) Nickel-iron (Fe/NiOOH)

This is another system similar to NiCd, but cheaper. It is a very rugged, long life system, capable of over 1250 deep discharge cycles. The energy density is similar to that of NiCd but the power density is appreciably lower. Nickel-iron produces hydrogen from corrosion reactions during both charging and discharging, making regular water addition necessary. If used in conjunction with a fuel cell, then the evolved hydrogen could be put to use and the water from the fuel cell could be used to top-up the battery. Eagle-Picher has recently developed a battery for traction use. Although these batteries are not as high power as NiCd or lead-acid, they do not contain toxic heavy metals, so environmental legislation could make this couple more popular. From the point of view of the CF, watering of the batteries could involve extra maintenance. On the other hand, the batteries last much longer than lead-acid and are cheaper than NiCd. DND should keep a watching brief on this technology, as a lower cost alternative to some of the other new systems, such as nickel-metal hydride.

d) Metal-air batteries (Zn/O_2 and Al/O_2, etc.)

Metal-air batteries make use of the air electrode technology developed for fuel cells. Such batteries can be very high energy density because only the metal is stored in the cell. Possible metals, in decreasing order of energy density are: lithium, aluminium, magnesium, calcium, iron and zinc. Some of these systems are only useful as primary batteries because of difficulty to recharge. Other systems are mechanically rechargeable (also called semi fuel cells, e.g. aluminium/air), rather than electrically rechargeable, making them useful for electric vehicle application. These batteries are also subject to the environmental conditions: in dry weather the electrolyte can dry out, plus in humid weather the air electrode may become saturated with water and reduce the power. Aluminium-air and zinc-air are the main systems to have been developed. These usually use an alkaline electrolyte, which means that corrosion can be a problem. Therefore, new batteries may be reserve format, whereby electrolyte needs to be added to activate them: thereafter, corrosion will be a problem at open circuit.

Canada has been instrumental in the development of these batteries. Initial work began with Alcan International Ltd. and the work is now carried on by Fuel Cell Technologies Ltd. in Kingston, ON and Alupower Inc. in Connecticut. These companies have sold telecommunications reserve power units that can provide 1200W for 48 hours and buoy batteries that use seawater. The Canadian Navy has also sponsored the development of a 2 kW, 100 kWh aluminium-air battery for air independent propulsion (AIP), which could find use in unmanned underwater vehicles (UUVs), long-range torpedoes or swimmer delivery vehicles. Here, the oxygen can be stored as compressed gas or as hydrogen peroxide. Canadian Navy funding for this development has now been cut, but the Massachusetts Institute of Technology is continuing funding for a UUV to travel under the Arctic ice cap. The batteries are mechanically rechargeable, whereby the spent aluminium electrodes and the electrolyte are replaced. Aluminium can be recovered from the spent electrolyte, where it is present as the hydroxide. DND should keep a watching brief on this technology.

Large, electric vehicle zinc-air batteries are being commercialized. The zinc-air system can be mechanically or electrically recharged. The systems suffer from corrosion of the metal to produce hydrogen and are low power. DND should keep a watching brief on the technology.

e) Nickel-zinc (Zn/NiOOH or NiZn)

Nickel-zinc appears to be a good candidate to replace NiCd, because zinc is a much lighter metal and is not toxic. The electrolyte is, again, alkaline and the open circuit voltage is higher than those of NiCd and NiMH are. The reason that NiZn is not already in widespread use is that zinc is very slightly soluble in the electrolyte, so the electrodes tend to change shape during cycling, growing long dendrites that can short-circuit the electrodes. Recently, a company in the USA (Evercel Inc.) has overcome these problems and developed a cell with a cycle life of over 600 cycles. The batteries are initially being marketed for electric scooters and bicycles. The data sheets for these cells quote the low temperature performance limit as –10°C, although the electrolyte is the same as for NiCd. DND should keep a close eye on this technology and should investigate the properties of the system, as a replacement for NiCd in the future.

f) Lithium-iron sulphide [Li(Al)/FeS$_2$]

Lithium-iron sulphide batteries operate at approximately 400°C and use a molten salt as electrolyte. Because this temperature is above the melting point of lithium, an alloy with aluminium is used. The batteries are being developed for electric vehicle use by the US Advanced Battery Consortium and they have good cycle life and energy density. Containment could be an issue for military use. DND should keep a watching brief on the technology.

g) Silver-zinc (zinc/silver oxide, Zn/AgO)

This couple has already been discussed as a primary system. As a secondary system it also has high energy density and a very high power density for an aqueous couple. It is still expensive because of the silver, although recycling offsets the cost. Unfortunately the cycle life is also low, with only 40 to 50 full discharges obtained, or approximately 100 to a depth-of-discharge of 60%. Silver migration through the separator is a problem with all silver-based couples, leading to eventual short-circuiting. In addition, zinc is very slightly soluble and zinc tends to redeposit towards the bottom of the cell, causing the electrode to grow and eventually pierce the separator. With overcharging the situation is worse because the deposits tend to be needle-like. Because of the high cost, typical applications are in submarines, torpedoes and in space. Due to the limited application of these batteries and the fact that research and development is carried out by the allies, no research by DND is being proposed. In North America, research is currently sponsored by NASA and the USN.

h) Lead-acid (Pb/PbO$_2$, Pb-acid)

Lead-acid batteries come in various versions: they can be flooded-electrolyte, gelled electrolyte, sealed (starved electrolyte); and the electrodes may be flat plate or spirally wound. Lead-acid batteries have a finite cycle life and do not like to be deeply discharged or stored in a discharged state (unlike NiCd). Although they have a low energy density, they can generate high power at low temperature, plus they are inexpensive and are easy to recycle upon disposal. Lead-acid batteries are so reliable that people tend to forget about them and take them for granted. Many of the problems in CF probably arise from lack of full recharging after use. There are a lot of additives in lead-acid batteries and battery performance has steadily improved over the years. This is a mature technology whose industry has its own large research groups, so DND does not need to carry out basic research on this couple. Much of the recent research has been aimed at electric vehicles and standby power.

i) Sodium-sulphur and sodium metal chloride (Na/S and Na/$NiCl_2$)

Sodium -sulphur batteries have been under development for over 25 years and sodium-metal chloride for about 15 years. Both of these are high energy density, but they contain molten sodium, so they are high temperature systems. These batteries have been demonstrated in electric vehicles and proposed for use in tanks, submarines and surface ships. The cell reactants are cheap. However, the highly reactive molten sodium does not seem to be compatible with the battlefield. DND should keep a watching brief on this system.

j) Lithium-ion and lithium-ion polymer

Large, spirally wound lithium-ion cells have been made for research into electric vehicles, for autonomous underwater vehicles and unmanned air vehicles, plus for standby power. The safety issues that apply to the small portable cells are exacerbated in large cells. Again, protective circuitry is required to maintain a safe voltage window. Because of the large size, heat management will be a problem. Lithium-ion polymer cells could also be manufactured in large format, once that they have been established for small format batteries. Both types are likely to be expensive. The automotive industry is planning to switch from a 12V to a 42V operating system, possibly as early as 2003, which would benefit high power lithium-ion batteries.

2.2 Technology Trends

This section will consider possible uses of the various battery couples in the CF and possible areas of pure and applied research. Battery couples that are already in widespread use in the CF are not being considered here, nor are couples that have already been identified above as providing no performance, environmental, or cost advantage, or are considered dangerous for general usage.

2.2.1 Trends in Primary Battery Technology

a) Development Of Lithium Pouch Cells

The reformatting of lithium primary batteries into a "pouch" format is an important recent development. These cells potentially offer higher energy density and the ability to adapt the shape of the cell to meet available space. Pouch cells using this couple are already under development by Eagle-Picher, Canada for the US Land Warrior.

b) Zinc-Iron Cells

The development of a new primary battery based on the zinc-iron couple has been reported recently. This system could provide a superior replacement for the widely used zinc-alkaline manganese dioxide cells, but little is known about it so far. DND could carry out basic studies on the electrochemical properties of this couple.

2.2.2 Trends in Portable Rechargeable Battery Technology

a) Nickel-Metal Hydride

There is considerable interest in nickel-metal hydride batteries as a replacement for the nickel-cadmium system, which is widely used at the present time. NiMH cells can have 50% more capacity than NiCd, but they are also correspondingly more expensive. In addition, NiMH has a fairly high self-discharge rate. NiCd cells, however, may be phased out because of environmental concerns over the disposal of cadmium.

b) Lead-acid

The Bolder Batteries lead-acid cells have very high power and could find application in devices requiring high current pulses. These batteries are a recent development and are not in widespread use yet. DND should keep a watching brief on the technology and investigate specific applications. The alternative power sources for pulse power are an established battery system coupled to a supercapacitor.

c) Lithium-ion and lithium-ion polymer

Lithium-ion batteries may predominate in the future. Industry is investing heavily in development for the commercial market. The final format of the cells is not yet known: they may have traditional cylindrical metal cans (lithium-ion) or they may be pouch format (lithium-ion polymer).

d) Lithium metal anodes

Advanced rechargeable batteries always have higher energy or power densities than the systems that they replace. In order to improve upon the energy density of lithium-ion cells appreciably, one needs to use a metal electrode, such as lithium, magnesium or aluminum. Lithium is the only one of these that recharges easily at room temperature, but it was not safe in early development versions.

2.2.3 Trends in Large Secondary Battery Technology

The following systems may be considered as possible replacements for the lead-acid and NiCd batteries that are presently in service. It should be appreciated that some of the present battery problems that the CF experiences are due to inadequate battery charging and maintenance, such as not fully recharging after a mission. Such problems do not necessarily go away by using a different battery couple, although it should be said that lead-acid batteries in particular deteriorate from being left in a low state-of-charge.

e) Nickel-metal hydride

Nickel-metal hydride batteries may replace NiCd and lead-acid batteries in the future for starting and emergency systems for land and air vehicles. However, they may never have as good performance at –40°C and they are more expensive. DND could investigate alternative metal hydride materials for low temperature operation; however, it may prove to be that hydrides which are better at low temperature, happen to have faster self-discharge rates at room temperature.

f) Metal-air batteries

Large, mechanically rechargeable metal-air batteries may find application in the Land Forces as quiet, two-man portable power sources for remote applications. Other possible applications include air-independent propulsion for submersibles. The systems can be considered as semi-fuel cell, but they may be cheaper and more robust than fuel cells.

g) Nickel-zinc

The nickel-zinc couple is low cost and may displace NiCd in the future. DND could sample the current technology in order to determine whether it has the potential to meet military requirements, especially low temperature performance. DND could also carry out research aimed at increasing the cycle life of these cells through the use of additives to the electrolyte or to the zinc electrode. Energy Ventures Inc. is a small battery research company based on the NRC campus in Ottawa that aims to license its technology to manufacturers. DND could collaborate with this company. The degree of risk is considered to be small because DND may be forced to replace NiCd batteries in the future, under environmental legislation.

h) Lithium-ion

Scaling up lithium-ion technology to large batteries is an engineering problem that is being dealt with by the battery industry. These batteries have a higher internal resistance than lead-acid batteries, so heat management will be a problem. In the event of a serious problem, these batteries will catch fire (but so can a tank of gasoline). Low temperature performance is a problem. DND should keep a watching brief on the technology.

2.3 Research and Development Opportunities

2.3.1 Recommendations for Portable Primary Batteries

Table 8 (p. 46) summarizes all of the recommendations and uses of primary batteries. It is considered that there are two main battery projects to pursue. The first is the development of a pouch style, lithium primary battery, using a solid cathode material such as manganese dioxide (which is cheap and readily available), with the understanding that this may not be able to replace lithium-sulphur dioxide below –20° to –30°C. The second project is to thoroughly investigate the zinc-iron system, which is a possible replacement for zinc-alkaline manganese dioxide batteries.

2.3.2 Recommendations for Portable Secondary Batteries

Table 9 (p. 47) summarizes the recommendations and uses of portable secondary batteries. DND should be investigating ways of improving the low temperature performance of existing couples by modifying the electrolyte or the electrodes. Such work could be carried out for nickel-metal hydride and lithium-ion/lithium-ion polymer. Several couples use the same nickel oxide electrode; this suffers from self-discharging at elevated temperatures, which limits the performance. Research could be undertaken to identify the degradation mechanisms and to develop chemical additives to lower the self-discharge rate. Another approach is to couple these batteries with supercapacitors to provide pulse power at low temperatures. For the longer term, research into lithium metal batteries should also be initiated. All of these recommendations should be undertaken.

2.3.3 Recommendations for Large Secondary Batteries

Table 10 (p. 48) summarizes the recommendations and uses of large format secondary batteries and supercapacitors. The driving force for commercial large battery research is electric vehicles, so the battery industry is investing heavily in research. From this point of view DND should keep a watching brief on the various technologies, but it should also sample all of the couples mentioned above, especially metal-air for remote power and nickel-zinc as a low cost replacement for NiCd. It is expected that cost may be an issue with respect to whether existing lead-acid and NiCd batteries can be replaced by other battery couples. COMINCO has the main lead-acid research group in Canada, located in Mississauga. This group is allied with the Advanced Lead Acid Battery Consortium, which has focussed on the use of lead-acid batteries for electric vehicles; in particular high-rate charging. It is not envisaged that DND should officially collaborate with COMINCO, although personal contacts are kept up. INCO also has a battery research laboratory adjacent to the COMINCO one. INCO specializes in powdered nickel hydroxide for the various alkaline nickel oxide couples. INCO is a major player in this area and no formal collaboration with DND is anticipated. Therefore, the main couples for DND to invest research in are nickel-metal hydride and nickel-zinc.

2.3.4 Conclusions

The CF use a wide variety of primary and secondary batteries of various sizes and electrochemical couples. No single battery couple is going to replace all of these. The battery industry is developing several different primary and secondary systems and DND is likely to purchase 2 or 3 of these during the next decade, as well as supercapacitors. Consequently, battery research should not all be concentrated on one particular system. At least three systems need to be investigated in detail; one for each of the three classes of battery discussed above. The most important systems for research are considered to be: portable zinc-iron and lithium-manganese dioxide pouch primaries, portable lithium-ion pouch secondaries, and large format nickel-zinc secondaries. Hybrid systems with supercapacitors also need to be investigated. Singling out two of these systems for more detailed attention we have lithium-ion pouch cells for portable systems and nickel-zinc large format batteries. Work on these systems will include the synthesis of high surface area, nanostructured materials, using sol-gel techniques.

2.4 Battery State-of-Charge and State-of-Health

Apart from battery chemistry, DND needs to investigate smart chargers and cables, smart batteries, methods of charging, state-of-charge determination, and state-of-health monitoring techniques. These are discussed in the following subsections.

2.4.1 Battery Charging

Battery charging is becoming increasingly important in the military, especially for portable batteries where there is increasing use of rechargeable batteries over non-rechargeable ones. Added to that is the introduction of new battery couples. For example, the Land Forces recently acquired a batch of nickel-metal hydride batteries for the thermal weapon sight, but the recently-fielded Iris battery charger-analyzer is only programmed for nickel-cadmium batteries. Nickel-metal hydride batteries can be charged with the Iris charger, but not properly or safely. There is a trend towards so-called smart batteries and smart chargers. The Iris charger incorporates some smart features, but it does not monitor the battery temperature, which is a major drawback in this area.

Smart batteries have an embedded, or attached, microchip that performs smart functions, such as bypassing those cells that become charged before the others in a battery. These chips are cheap, but are still not cost-effective if the battery itself is low cost. At the present time, most of the smart batteries available are lithium-ion, because this is an expensive battery couple to begin with and needs to be cycled within specific voltage limits. Smart chargers are the second approach, which is less expensive but does not allow the monitoring of individual cell voltages in the battery pack. The types of information and properties to be incorporated into the chip for a battery are: battery type, model and serial number; state-of-charge, cycle number and number of full and partial charges and discharges; control of power for charging and cell balancing; fault protection and the maximum and minimum temperatures that the battery has ever been exposed to; termination of charging and discharging through measurement of voltage, temperature or pressure. The above list does not include all of the possibilities.

The method of charging itself is very important and is not the same for all battery couples. Many systems are being found to have a longer service life when subjected to high-rate pulsed charging, although this does need to be monitored closely. One version of this is termed reflex charging, whereby a charging pulse is followed by a brief open circuit stand during which the resistance-free voltage (no iR drop) can be measured, then a very brief discharging pulse. The latter pulse has the effect of reversing the concentration gradients in the electrolyte and also helps to remove any large crystal of active material on the electrodes. The majority of work done so far has been on the nickel-cadmium system, with some work done on lead-acid. Sulphation is a problem with lead-acid and it has been suggested that pulsed charging can reduce sulphation. DND has expertise in this area and it may be possible to incorporate pulsed charging into routine charging of vehicle batteries, via the use of a capacitor. It is suggested that DND carryout some work in this area because of the large number of vehicle batteries in use that could benefit.

With a new system, such as nickel-metal hydride or lithium-ion, the optimum method of charging, from the point of view of long term retention of capacity, may not yet have been established. Feedback charge control is an important function of a chip here. The method of charging of lithium-ion batteries may be particularly important because these tend to irreversibly lose capacity with use, unlike nickel-cadmium batteries where capacity can be recovered from reconditioning cycles. For fast charging of aqueous systems, one can charge with high current pulses that are applied until the voltage increases to close to the oxygen gassing voltage, then go to open circuit. Current can be applied in this way several times per second. High rate charging may lead to other problems if cells are out-of-balance. One of the variables to consider is the actual shape of the waveform used to provide the pulses to the battery, since the optimum is not necessarily a rectangular waveform. Pulsed charging needs to be investigated in more detail for use in future chargers for the CF. Although rapid pulse charging is efficient with new batteries at room temperature, it will have problems at low temperatures, where production of hydrogen is likely to be one of the problems. A smart charger might initially apply a low constant current charge in order to warm the cells, before applying any pulses. Another approach to rapid charging is to charge to 90% and then stop. This is because overcharging can be detrimental to the service life of a battery, so it should last longer with a 90% charge. The battery can receive a full charge, at a lower rate, every tenth cycle in order to exercise it fully.

Reconditioning of sealed nickel-cadmium batteries using a charger-analyzer has been shown to lead to less battery wastage in the US Navy. The Iris charger-analyzer has a reconditioning cycle that does not function correctly and the electrochemical power sources group has advised PMO TCCCS on modifications to the charger, which are currently underway. The modifications will prevent a lot of wastage in the future and further modifications will be necessary when other battery types are introduced. The present expertise in battery charging should be maintained and DND should examine the different ways of charging new battery couples. Cadex Inc. of Vancouver manufactures charger-analyzers for indoor use with NiCd, NiMH and lead-acid portable batteries and has a major share of the North American market for emergency services, hospitals and large industrial complexes. The Iris charger-analyzer was built by KB Electronics of Halifax. Both of these companies could make use of any improved charging techniques discovered in work carried out by DND, which would benefit the CF in future battery chargers.

2.4.2 State-of-Charge

Knowing the state-of-charge of a battery can be crucial before going out on a mission. Batteries that give a very steady voltage throughout their discharge (a flat discharge curve) are good for the equipment but do not warn the user of imminent, rapid loss of voltage at the end of discharging. The lithium-liquid cathode systems all have very flat discharges, while nickel-cadmium is almost flat for about 70% of the discharge and lead-acid is not much better. In contrast, alkaline zinc and lithium-ion batteries have continuously falling voltages that make the estimation of the state-of-charge much easier.

Lithium-sulphur dioxide batteries are particularly troublesome because a soldier will not want to carry extra BA5590's unnecessarily and he may mistakenly discard one that is only 30% discharged. There are ways to count the quantity of charge extracted from the battery using a chip (called a gas gauge), but this is extra expense for an already expensive throwaway battery. An alternative could be to use a smart cable from the battery to the equipment, so that the chip is not part of the battery. The chip could be encoded to give an audible warning when 90% of the rated capacity for the ambient temperature has been consumed, for example. An interface switch could also be used to sense the battery connector as to whether the battery is rechargeable or non-rechargeable.

Lead-acid batteries have always been difficult to monitor accurately. Submarine batteries and those used for silent watch in an APV are important examples. Novel ways of monitoring the state-of-charge need to be investigated in order to improve reliability. Some such work is currently underway in the EPSG, using wire-wound coils and high frequency AC current to monitor the change in the quantity of lead in the end plate of the battery. The importance of this technique lies in the fact that the coils are external to the battery. This work should continue and be extended to other battery systems.

2.4.3 State-of-Health

The EPSG has historically been engaged in state-of-health research (e.g. infrared imaging, voltage noise, reactivation of passivated lead-acid batteries) and it is anticipated that such work will continue, especially since new battery types will be introduced which will have their own idiosyncrasies. Again, microchips are likely to play a large role here for monitoring, for example, the cell-to-cell variation in temperature in a battery. The type of research to be performed here will depend on the battery types brought into service, such as lithium-ion polymer. Anticipated problems with these are an increase in internal resistance with aging and, possibly, gassing. Studies should be conducted as necessary.

2.4.4 Safety studies

Safety is of paramount importance with all batteries and particularly so for portable systems. Whilst safety studies themselves do not always constitute basic research, research that is carried out on the various battery couples is used to determine what types of safety testing needs to be applied to a new battery. With the introduction of new battery types and their extra electronics, it is anticipated that work by the EPSG in this area will continue.

2.5 Laboratory Synthesis of Nanostructured New Materials

This section outlines the general approach that will be taken to in-house synthesis of new materials for batteries and supercapacitors. Nanostructured materials will be made using aerogel and xerogel techniques, as described below.

In order for a battery or a supercapacitor to sustain high currents without a large voltage drop, the electrolyte and the electrodes need to have good conductivity, the electrode structure needs to be porous, and the surface area needs to be as large as practical without the structure becoming unstable. In recent years, laboratory syntheses have resulted in a wide variety of materials being produced by various techniques, where the scale of the particles produced are of the order of nanometers. In the case of carbon, there was the discovery of Buckmeisterfullerenes (Buckeyballs), which are a highly structured spherical arrangement of 60 carbon atoms. These are produced in an electric arc at a yield of about 2% and need to be separated from the accompanying 98% soot. Consequently, this material is too expensive for possible battery use, but there are other structured forms of carbon. Carbon nanofibres and nanotubes are now available. These are cheaper, although the nanotubes are still expensive. Carbon nanofibres are being used in lithium-ion battery research and the nanotubes in hydrogen storage research. A much cheaper form of nanostructured carbon is in the form of an aerogel. Gels are a 3 dimensional network of a solid dispersed in a solvent, typically water. When a gel is dried in air, the resulting opaque solid is called a xerogel. The gels shrink during the drying process but the xerogels still contain solvent trapped in pores in the structure. Aerogels are gels that have had their solvent extracted at the supercritical point using a pressure vessel. In this way minimal shrinkage occurs and a very porous, low-density structure is obtained. Carbon aerogels are made using controlled pyrolysis of a gel made from the polymerisation of resorcinol (1,3 dihydroxybenzene) in formaldehyde. This yields a very porous honeycomb structure. By controlling the ratio of the reactants and the pyrolysis temperature, it is possible to tailor the particle size and porosity of the carbon to suit a particular application: in our case electrochemical. Carbon aerogels can have surface areas in the region of 400 to 1000 m^2/g and pore sizes in the range of 30A to 500A. DND already has expertise in this area, residing with the carbon group at the RMC, which has links established with the EPSG group at the NRC. This collaboration will initially lead to the production of carbon electrodes for supercapacitor research. The EPSG also has prior experience in synthesizing vanadium pentoxide xerogels, so is well positioned to apply the methods to other battery or fuel cell related materials. One problem with inorganic aerogels and xerogels is their low conductivity. Ways to overcome this problem will be investigated. One possibility will be to form the gel in the presence of nickel nanowires, which could provide both conductivity and stability to the structure.

One needs to determine whether nanostructures are appropriate to a given battery couple. For example, nanostructured lithium metal could be prepared but lithium is very reactive so it might spontaneously ignite upon contact with a non-aqueous electrolyte (it would certainly ignite upon contact with water, unlike a smooth ribbon of lithium). Also, battery couples that involve the formation of new solid products, of different crystal structure to the reactants, may not be candidates because the original structures could disappear after the first cycle. This would not be a problem for electrodes that become intercalated though, such as the electrodes in lithium-ion batteries. Thirdly, with respect to battery operation, high surface area of nanoparticles could lead to higher self-discharge rates during storage. Therefore, nanostructured materials will not be the optimum solution in all cases and it is important to understand the nature of the possible problems that need to be overcome during research.

Apart from cost being an issue, there will be the stability of nanostructured electrodes to shock and vibration in service and whether they can be cycled many times in rechargeable cells without degradation in structure, surface area and porosity. Such degradation could arise from swelling and shrinkage of the particles as they are electrochemically cycled and also because of partial solubility. Most solids have some degree of solubility and those that have a very low solubility tend to dissolve then reprecipitate nearby. In the case of crystals, this process leads to crystals increasing in size and this is referred to as ripening (NiCd and lead-acid batteries are examples of where crystal growth does occur). The rate of dissolution of a solid will increase with its surface area, so nanostructures will dissolve more quickly. Ideally, nanostructured solids need to be completely insoluble in the electrolyte being employed. This means that the electrolyte usually used with a particular battery couple may need to be modified or replaced. A different approach to this problem is to use an additive in the electrode material that would inhibit dissolution.

There is likely to be a trade-off between the properties of the nanostructured solid and those of the electrolyte. The highest surface area electrode material possible may not be the best one to use because of mechanical and solubility problems, and the most conducting electrolyte may not be the optimum to use because of partial dissolution of the electrode material. As regards non-aqueous systems, which are typically one order of magnitude less conducting than aqueous ones, having electrodes that can accommodate very high currents is of no use if the electrolyte cannot support the same high currents, or gets very hot from resistive heating during operation. Therefore, the research program will address these issues.

Lithium-ion battery electrodes could benefit from nanotechnology. In fact, one research group in the USA has already made nanostructured lithium manganese oxide using a polycarbonate membrane as a template that was later dissolved away. So far, these electrodes have been successfully cycled in an aqueous electrolyte. The rate used was typically the 11C rate (11 times the current at which the battery takes one hour to discharge), but the thinnest wall fibres made could support 109C. High rates were obtained because the high surface area meant that the diffusion of lithium ions into and out of the crystal lattice (relatively slow) was not so important. Carbon fibres are already available for use as the negative electrode, but the main problem is probably the electrolyte resistance. Another possible candidate for nanostructures could be the metal hydride electrodes of nickel-metal hydride batteries. This could enable faster insertion and removal of hydrogen. Again, a high self-discharge rate could be a problem, but research will need to be done in order to establish the actual behavior. In summary, the battery research program will include the synthesis of new, nanostructured electrode materials using aerogel and xerogel techniques and possibly techniques involving the use of a template.

Finally, mention should be made of microbatteries, which can be fabricated on a chip and may find application with MEMS devices. So far, lithium-ion and nickel-zinc batteries have been fabricated, with limited success because of loss of solvent. DND does not have the facilities for such work, but the Ottawa area does have companies that could.

Table 5: Properties of Selected Primary Batteries

Cell Couple	OCV[a]	NLV[b]	Energy density[c]		Power density (cont.)	Temperature range	Discharge profile	D Size	
	(V)	(V)	(Wh kg^{-1})	(Wh dm^{-3})	(W kg^{-1})	(°C)		Wt (g)	cap (Ah)
Zn/air	1.45	1.5	340	1050	40	0 to 50	Flat	-	-
Zn/MnO$_2$ (NH$_4$Cl)	1.5	1.25	65	100	2	-5 to 45	Sloping	85	4.5
Zn/MnO$_2$ (ZnCl$_2$)	1.5	1.25	85	165	4	-10 to 50	Sloping	93	7.0
Zn/MnO$_2$ (alkaline)	1.5	1.25	125	320	7	-30 to 55	Sloping	132	14
Zn/Ag$_2$O (button)	1.6	1.6	120	500	7	0 to 55	Flat	-	-
Li/FeS$_2$ (AA size)	1.8	1.5	235	425	150	-40 to 60	Sloping	-	-
Mg/MnO$_2$	1.9	1.8	100	195	7	-20 to 60	Sloping	105	7
Li/SO$_2$	2.9	2.75	250	400	140 650*	-50 to 70	Flat	85	7.5
Li/CF$_x$	3.0	2.8	360	680	14	-40 to 85	Flat	93	12
Li/V$_2$O$_5$	3.4	3.3, 2.4	120, 260	300, 660	11	-30 to 50	Two Plateaux	-	-
Li/MnO$_2$	3.4	2.8	280	580	50	-30 to 70	Sloping	105	10
Li/SOCl$_2$	3.65	3.5	290	670	105 2500*	-40 to 85	Flat	100	13
Li/SOCl$_2$, BrCl	3.9	3.7 to 3.8	350	770	75	-40 to 70	Initially sloping	121	13
Li/SO$_2$Cl$_2$	3.95	3.7	330	720	100	-30 to 90	Flat	122	13

[a] Open circuit voltage [b] Nominal load voltage [c] Practical energy density. This is only a rough guide and corresponds to a moderate load. The value will vary with the load, temperature and depth of discharge.
* = 1 second pulses

Table 5 Properties of selected primary (non-rechargeable) batteries. The data in the top half of the table are mainly for low-rate bobbin design cells, whilst the data in the bottom half are all for high-rate spirally wound cells. Therefore, the power densities are not strictly comparable. The aqueous couples are not normally available in a high-rate format because of the extra expense in manufacture, which makes them uncompetitive with the non-aqueous systems. The power densities are for continuous operation and are based on the available data. They are only a guide based on safe operation, and the values also depend on the surface areas of the electrodes used.

Table 6: Properties of Selected Portable Secondary Cells

Cell Type	Open Circuit Voltage V	Cycles	Energy Wh/kg	Density Wh/l	Pulse Power W/kg (1s pulse)	Advantages	Disadvantages
Cd/NiOOH sealed	1.25	300-700	35	105	210	well known excellent power high cycle life	low energy density Cd is toxic
Zn/MnO$_2$ bobbin	1.25	55	60	130	low	well known, very cheap	corrosion of Zn
MH/NiOOH	1.4	1000	80	240	n/a	high cycle life excellent power capability	poor shelf life Expensive, but cheaper than Lithium-ion high self-discharge
Pb/PbO$_2$ Bolder	2.1	650-800	28	68	>1600	excellent power	low energy density
Lithium-ion	4.2	1000	150	390	400	high energy density high cycle life	costly sloping voltage
Lithium-ion polymer flat plate	4.2	>300	190	470	n/a	high energy density pouch format, any shape	costly sloping voltage poor at low temp.

Table 6: Performance, advantages and disadvantages of selected portable secondary cells. The power densities are only a rough guide because the power generated decreases with the time at high discharge rates, as well as temperature: some couples can generate kilowatt/kilogram pulses on a millisecond timescale. All cells are spirally wound format, unless stated otherwise.

Table 7: Properties of Selected Large Format Secondary Cells

Cell Type	Open Circuit Voltage V	Cycles	Energy Wh/kg	Density Wh/l	Power from a 30s pulse W/kg	Advantages	Disadvantages
$Cd/NiOOH$	1.25	500-2000	40	100	460	well known excellent power	low energy density memory effect Cd is toxic
$MH/NiOOH$	1.4	1000	80	240	150	high cycle life excellent power capability	poor shelf life expensive high self-discharge
$Fe/NiOOH$	1.4	4000	30	60	100	rugged long life	low energy and power densities, high self-discharge
Al/air	1.4	-	250	200	-	high energy density	sensitive to humidity need infrastructure to refuel
$Zn/NiOOH$	1.6	600	70	130	300	non-toxic high energy density	low cycle life
Zn/air	1.6	-	150	160	95	cheap, high energy density	sensitive to humidity need infrastructure to refuel
$LiAl/FeS_2$	1.7	600	180	150	400	high energy density, cheap materials	high temperature system
Zn/AgO	1.85	10-50	90	180	500 2000*	high energy density good shelf life	costly low cycle life
Pb/PbO_2 Optima, SLI	2.1	650-800	52	120	600	well known excellent power cheap	low energy density
Na/S	2.1	-	170	250	390	high energy density, cheap materials	high temperature system, needs containment
$Na/NiCl_2$	2.5	-	125	190	-	high energy density	high temperature system, needs containment
Lithium-ion	4.2	1000-3500	150	300	400	high energy density high cycle life	costly sloping voltage

Table 7: Performance, advantages and disadvantages of selected large format secondary cells. Couples that appear here as well as in Table 6 have different properties because of being different format e.g. flooded electrolyte instead of starved. The power densities are only a rough guide.
* = especially designed high-power battery.

Table 8: Summary of Recommendations and Uses of Primary Batteries

PRIMARY BATTERIES	ACTION	COMMENTS	APPLICATION	CANADIAN COMPANIES	COST OF RESEARCH (CAN$)
PORTABLE					
zinc-air, lithium-air	watching brief	low cost but not low temperature	Land Forces training, communications.	none	
lithium-thionyl chloride	watching brief	good low temperature performance, but safety issues for high rate cells.	remote sensing	none	
lithium-carbon monofluoride	watching brief	possible replacement for lithium-sulphur dioxide, but lithium-manganese dioxide probably better.	communications	none	
lithium-manganese dioxide pouch cells	improve low temperature performance	lower cost and higher energy density replacement for lithium-sulphur dioxide. Performance poor below -20°C. Not pressurized. Possible fire hazard.	communications, soldier systems	Eagle-Picher, Canada (BlueStar)	400k over 2 years
zinc-iron	investigate basic chemistry and low temperature performance	at early research stage. Possible replacement for alkaline-zinc.	flash lights and general use	none	200k over 2 years
lithium-iron disulphide	investigate commercial cells	possible replacement for alkaline-zinc for low temperatures and higher rate.	flash lights and general use	none	
THERMAL	watching brief	high temperature molten salt systems	missiles, torpedoes, ejection seats.	none	

Table 9: Summary of Recommendations and Uses of Portable Secondary Batteries

SECONDARY BATTERIES	ACTION	COMMENTS	APPLICATION	CANADIAN COMPANIES	COST OF RESEARCH (CAN$)
PORTABLE					
nickel-metal hydride	improve self discharge of nickel oxide and metal hydride electrode materials. Improve low temperature performance.	possible replacement for all sealed nickel-cadmium batteries, but is in competition with lithium rechargeables.	Land Forces soldier systems, training, communications.	INCO for nickel powder and nickel hydroxide.	900k over 3 years
lead-acid	investigate for pulsed power applications.	very high power density spirally wound cells, good low temperature performance.	electronic guns and other weapons.	none. Made by Bolder Batteries, Colorado.	minor project
lithium-ion	find improved, lower cost cathode materials	possible replacement for all sealed nickel-cadmium batteries, but is in competition with nickel-metal hydride.	Land Forces soldier systems, training, communications.	Eagle-Picher, Canada (BlueStar)	300k over 3 years
lithium-polymer	watching brief	system developed by Hydro-Quebec no good at low temperature, lithium dendrites a problem.	Land Forces soldier systems, training, communications.	Hydro-Quebec (research previously funded by DND)	
lithium-ion polymer	improve low temperature performance, hybrid with supercapacitor.	plastic pouch format – easy to build any shape and size. Possible replacement for all sealed nickel-cadmium batteries.	Land Forces soldier systems, training, communications.	Electrofuel Inc., Toronto.	300k over 3 years
lithium-metal	investigate suppression of lithium dendrites and other ways to make cycling safe	higher energy density and higher rate than lithium-ion	Land Forces soldier systems, training, communications.	none	150k over 3 years

Table 10: Summary of Recommendations and Uses of Large Format Secondary Batteries and Supercapacitors

SECONDARY BATTERIES	**ACTION**	**COMMENTS**	**APPLICATION**	**CANADIAN COMPANIES**	**COST OF RESEARCH (CAN$)**
LARGE FORMAT					
nickel-metal hydride	see Table 9	possible replacement for nickel-cadmium and lead-acid	starter, lights, ignition (SLI) and electric vehicle (EV)	INCO for nickel powder and nickel hydroxide.	see Table 9
nickel-iron	watching brief	possible replacement for nickel-cadmium and lead-acid	SLI and EV	INCO for nickel powder and nickel hydroxide.	
aluminium-air	watching brief	mechanically rechargeable. Previously funded by DND for air-independent propulsion.	UUVs, swimmer delivery vehicle, reserve power.	Fuel Cell Technologies, Kingston, ON.	
zinc-air	watching brief	mechanically or electrically rechargeable.	SLI and EV	Noranda, Quebec is a supplier of zinc.	
nickel-zinc	improve low temperature performance and cycle life	low cost, non-toxic replacement for nickel-cadmium and lead-acid.	SLI and EV	Energy Ventures, Inc., Ottawa.	200k over 2 years
lithium-iron disulphide	watching brief.	high temperature system	EV	none	
sodium-sulphur and sodium-nickel chloride	watching brief	high temperature system, safety issues	EV	none	
lithium-ion and lithium-ion polymer	watching brief	low temperature operation and safety are issues.	possible replacement for nickel-cadmium and lead-acid, but may be too expensive.	Eagle-Picher, Canada (BlueStar)	
SUPERCAPACITORS	research into carbon materials for low temperature and high current operation	used for high power pulses, hybrid with battery.	communications, electronic weapons, EV.	none	600k over 3 years

3 FUEL CELLS

A fuel cell is a power source (generator) that produces electricity. The basic fuels for this device are hydrogen and oxygen. A fuel cell is essentially a battery with an anode electrode, an electrolyte separator, and a cathode electrode, however the hydrogen is fed into the anode electrode, and the oxygen is fed into the cathode electrode. The hydrogen molecule is oxidized by the catalyst bed at the anode resulting in a release of protons that travel through the electrolyte separator to combine with the oxygen ion to form a water molecule. The electrons released by the hydrogen, travel externally from the anode electrode via an electric circuit to the cathode electrode to produce electricity. The basic electrochemical process is given by the equation:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + Heat + Electricity$$

Leaving aside practical issues such as manufacturing and materials cost, the two fundamental technical problems with fuel cells are the slow reaction rate, leading to low currents and power, and that hydrogen is not a readily available fuel. To solve these problems many different fuel cell types have been tried. The different fuel cell types are usually distinguished by the electrolyte that is used, though there are always other important differences as well. The situation now is that five classes of fuel cell have emerged as viable systems for the present and near future. Their operating characteristics are listed in Table 11.

Table 11: Fuel Cell Technology

Fuel Cell	**AFC**	**FAFC**	**MCFC**	**SOFC**	**PEMFC**
Power Range	Watt to kilowatt	Kilowatt to megawatt	Kilowatt to megawatt	Kilowatt to megawatt	Milliwatt to megawatt
Operating Temp range	Above 0 °C	Above 0 °C	Above O °C	Above 0 °C	-40 to 50 °C
Chemical reaction temp range	60 °C to 90 °C	180-210 °C	950 °C	1000 °C (1) 500 °C (2)	80 to 110° C
Specific Power	130W/kg(1)				3kW/kg (1) 5kw/kg(2)
Power density	90W/L				
Fuel cell efficiency	70% (3)	40% (3) 85% (4)		60% (3) 85% (4)	

Notes: (1) Present technology
(2) Technology within 5 years
(3) Balance of Plant
(4) Balance of Plant plus co-generation
(5) Alkaline fuel cell (AFC); Proton exchange membrane fuel cell (PEMPC); Phosphoric acid fuel cell (PAFC); Molten carbonate fuel cell (MCFC); and Solid oxide fuel cell (SOFC)

Not included in the above list are fuel cells that can use a fossil fuel directly without conversion to hydrogen, such as methanol. R&D into direct methanol fuel cells etc. is progressing to a point where suitable military applications can be available in 2020 if R&D continues to progress.

Advantages and Applications

The most important disadvantage of fuel cells at the present time is the same for all types is the cost. However, there are many military advantages, which feature more or less strongly for different types and lead to different applications. These include:

Efficiency: Fuel cells are generally more efficient than combustion engines whether piston or turbine based. A further feature of this is that small systems can be just as efficient as large ones. This is very important in the case of the small local power generating systems needed for combined heat and power systems.
Simplicity: The essentials of a fuel cell are very simple, with few if any moving parts. This can lead to highly reliable and long lasting systems.
Low emissions: The by-product of the main fuel cell reaction, when hydrogen is the fuel, is pure water, which means a fuel cell can be essentially "zero emission". This is their main advantage when used in vehicles, as there is a requirement to reduce vehicle emissions, and even eliminate them within cities. However, it should be noted that, at present, emissions of $C0_2$ are nearly always involved in the production of the hydrogen needed as the fuel.
Silence: Fuel cells are very quiet, even those with extensive extra fuel processing equipment. This is very important in both portable power applications and for local power generation in combined heat and power schemes.

The fact that hydrogen is the preferred fuel in fuel cells is, in the main, one of their principal disadvantages. However, there are those who hold that this is a major advantage. It is envisaged that as fossil fuels run out, hydrogen will become the major world fuel and energy vector. It would be generated, for example, by massive arrays of solar cells electrolyzing water. This may well be true, but is unlikely to come to pass within the next 20 years.
The advantages of fuel cells impact particularly strongly on combined heat and power systems (for both large and small scale applications), and on mobile power systems, especially for vehicles and electronic equipment such as portable computers, mobile telephones, and military communications equipment. These areas are the major fields where fuel cells will be used. A key point is the very wide range of applications of fuel cell power, from systems of a few watts up to megawatts.

3.1 State-of-the-Art

3.1.1 Alkaline Fuel Cell (AFC)

NASA developed the alkaline fuel cell for their space program. The alkaline fuel cell was used on the Apollo and Shuttle Orbiter craft. Although many of these systems worked reasonably well as demonstrations, other difficulties, such as cost, reliability, ease of use, ruggedness and safety were not so easily solved. When attempts were made to solve these wider engineering problems, it was found that, at that time, fuel cells could not compete with rival energy conversion technologies, and research and development was scaled down. The alkaline fuel cells played a hugely important role in keeping fuel cell technology development going through the later half of the 20th century. The success of the alkaline fuel cell in this application, and the demonstration of high power working fuel cells by Bacon, led to a good deal of experiment and development of alkaline fuel cells during the 1960s and early 1970s.

Overview

The basic chemistry of the alkaline electrolyte fuel cell (AFC) for the reaction at the anode is:

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

The electrons released in this reaction pass round the external circuit, reaching the cathode, where they react, forming new OH^- ions.

$$O_2 + 4e^- + 2H_2O \rightarrow 4OH^-$$

This fuel cell utilizes hydrogen as fuel, oxygen as the oxidizer, an aqueous sodium hydroxide or potassium hydroxide solution as the electrolyte. The electrochemical process typically operates at less than 100°C, thus the product water (H_2O) is in aqueous form and must be extracted from the fuel cell otherwise it can dilute the electrolyte. The problem of slow reaction rate is overcome by using highly porous electrodes, with a platinum catalyst, and by operating at quite high pressures. The temperature is higher than for the PEM fuel cell, but it would still normally be classified as a 'low temperature' cell. Innovative design and new material development have significantly reduced the corrosion caused by the hot alkaline electrolyte on the electrode and the structural. The system efficiencies ranges from 30 to 80% depending on the complexity on the fuel processing and waste heat recover in the balance of plant. Their main problem is that the air and fuel supplies must be free from CO, or else pure oxygen and hydrogen must be used.

3.1.2 Phosphoric Acid Fuel Cell (PAFC)

The phosphoric acid fuel cell (PAFC) was the first to be produced in commercial quantities and it enjoys widespread terrestrial use. Many 200 kW systems, manufactured by the International Fuel Cells Corporation, are installed in the USA and Europe, as well as systems produced by Japanese companies. Porous electrodes, platinum catalysts and a fairly high temperature (220 °C) are used to boost the reaction rate to a reasonable level.
The hydrogen fuel problem is solved by 'reforming' natural gas (methane) to hydrogen and carbon dioxide, but the equipment needed to do this adds considerably to the costs, complexity and size of the fuel cell. Nevertheless, they use the inherent simplicity of a fuel cell to provide an extraordinarily reliable and maintenance free power system. They have run continuously for over a year without any maintenance requiring shut-down or human intervention. As well as providing electricity it also provides about the same heat energy in the form of steam. Such units are called "combined heat and power" or CHP systems. The PAFC was developed commercially as prime power generation plants for municipal and remote sites, and as standby power generator for building and hospitals. The benefit in using phosphoric acid as the electrolyte is because it has higher tolerance to carbon dioxide in the hydrogen fuel stream. The PAFC is typically larger and heavier than the alkaline fuel cell but it has similar corrosion problem as the alkaline fuel cell.

Overview
The PAFC works in a similar fashion to the PEM fuel cell. The PAFC uses a proton-conducting electrolyte. In the PAFC, the electrochemical reactions take place on highly dispersed electrocatalyst particles supported on carbon black. As with the PEM fuel cells, platinum (Pt) or Pt alloys are used as the catalyst at both electrodes. The electrolyte is an inorganic acid, concentrated phosphoric acid (100%) which, like the membranes in the PEM cells, will conduct protons. Phosphoric acid is the only common inorganic acid that has good enough thermal stability, chemical and electrochemical stability and low enough volatility above about 150°C, to be considered as an electrolyte for fuel cells. Most importantly, phosphoric acid is tolerant to CO, in the fuel and oxidant, unlike the alkaline fuel cell. It is therefore necessary to replenish electrolyte during operation, or ensure that sufficient reserve of acid is in the matrix at the start of operation to last the projected lifetime.
Like the PEM fuel cell, the PAFC uses gas diffusion electrodes. Pt supported on carbon has replaced Pt black as the electrocatalyst, as for the PEMFC. The carbon is bonded with PTFE (about 30-50 wt%) to form an electrode support structure. The carbon has important functions:

- To disperse the Pt catalyst to ensure good utilization of the catalytic metal
- To provide micropores in the electrode for maximum gas diffusion to the catalyst and electrode/electrolyte interface
- To increase the electrical conductivity of the catalyst.

By using carbon to disperse the platinum a dramatic reduction in Pt loading has also been achieved over the last two decades - to about 0.10 mg Pt cm^{-2} in the anode and about 0.50 mg Pt cm^{-2} in the cathode.

Electrode performance does decay with time. This is due primarily to the sintering (or agglomeration) of Pt catalyst particles and the obstruction of gases through the porous structure caused by electrolyte flooding. The rate of this sintering phenomenon depends mainly on the operating temperature. An unusual difficulty is that corrosion of carbon becomes a problem at high cell voltages (above ~0.8 V). For practical applications, low current densities, with cell voltages above 0.8 volts, and hot idling at open circuit potential are therefore best avoided with the PAFC. The PAFC stack consists of a repeating arrangement of a ribbed bipolar plate, the anode, electrolyte matrix and cathode. A typical PAFC stack may contain 50 or more cells connected in series to obtain the practical voltage level required.
The ribbed substrate has some key advantages:

- Flat surfaces between catalyst layer and substrate promote better and uniform gas diffusion to the electrode
- It is amenable to continuous manufacturing process since the ribs on each substrate run in only one direction
- Phosphoric acid can be stored in the substrate, thereby increasing the lifetime of the stack

In PAFC stacks, provisions must be included to remove the heat generated during cell operation. This can be done by either liquid (water/steam or a dielectric fluid) or gas (air) coolants. Water cooling is the most popular method. Water cooling can be done with either boiling water or pressurized water. Boiling water cooling uses the latent heat of vaporization of water to remove the heat from the cells. But, pressurized water gives a better overall performance than using oil cooling or air cooling, though these may be preferred for smaller systems. The main disadvantage of water cooling is that water treatment is needed to prevent corrosion of cooling pipes and blockages developing in the cooling loops.

3.1.3 Molten Carbonate Fuel Cell (MCFC)

The molten carbonate fuel cell (MCFC) has the interesting feature that it needs the carbon dioxide in the air to work. The high temperature means that a good reaction rate is achieved using a comparatively inexpensive catalyst - nickel. The nickel also forms the electrical basis of the electrode. Like the SOFC it can use gases such as methane and coal gas (H_2 and CO) directly, without an external reformer. However, this simplicity is somewhat offset by the nature of the electrolyte, a hot and corrosive mixture of lithium, potassium and sodium carbonates. MCFC was developed to serve a similar market to the PAFC but at much larger power generation capacity. The electrolyte is in a form of molten potassium lithium carbonate. Its chemical reaction is typically at 650°C and can tolerate both carbon monoxide and carbon dioxide in the hydrogen fuel stream thus enabling the use of less sophisticated fuel processing plants.

Overview

The electrolyte of the molten carbonate fuel cell is a molten mixture of alkali metal carbonates - usually a binary mixture of lithium and potassium, or lithium and sodium carbonates, which is retained in a ceramic matrix of $LiAl0_2$. At the high operating temperatures (typically 600-700 °C) the alkali carbonates form a highly conductive molten salt, with carbonate ions providing ionic conduction. Note that unlike all of the common fuel cells, carbon dioxide needs to be supplied to the cathode as well as oxygen, and this becomes converted to carbonate ions, which provide the means of ion transfer between the cathode and the anode. At the anode, the carbonate ions are converted back into $C0_2$. There is therefore a net transfer Of $C0_2$ from cathode to anode; one mole of $C0_2$ is transferred along with two Faradays of charge or two moles of electrons. The overall reaction of the MCFC is:

$$H_2 + 1/2\ O_2 + CO_2\ (\text{cathode}) \rightarrow H_2) + CO_2\ (\text{anode})$$

Usually the $C0_2$ partial pressures are different in the two electrode compartments and the cell potential is therefore affected accordingly. It is usual practice in an MCFC system that the $C0_2$ generated at the cell anodes is recycled externally to the cathodes where it is consumed. At the operating temperatures of MCFCS, nickel (anode) and nickel oxide (cathode) respectively are adequate catalysts to promote the two electrochemical reactions. Unlike the PAFC or the PEMFC, noble metals are not required. Other important differences between the MCFC and the PAFC and PEMFC are the abilities to directly electrochemically convert carbon monoxide and internally reform hydrocarbon fuels.

In practical applications, it is most unlikely that pure CO would be used as fuel. More likely is that the fuel gas would contain both H_2O and CO, and in such cases the electrochemical oxidation of the CO would probably proceed via the water gas shift reaction.

Unlike the PEMFC, AFC, and PAFC, the MCFC operates at a temperature high enough to enable internal reforming to be achieved. This is a particularly strong feature of both the MCFC and the SOFC. Unfortunately, the higher temperatures also place severe demands on the corrosion stability and life of cell components, particularly in the aggressive environment of the molten carbonate electrolyte.

The PAFC and MCFC are similar types of fuel cell in that they both use a liquid electrolyte that is immobilized in a porous matrix. Electrolyte management, that is the control over the optimum distribution of molten carbonate electrolyte in the different cell components, is critical for achieving high performance and endurance with MCFCS. This feature is very specific to this type of fuel cell. Various undesirable processes (i.e. consumption by corrosion reactions, potential driven migration, creepage of salt and salt vaporization) occur, all of which contribute to the redistribution of molten carbonate in MCFCS.

3.1.4 Solid Oxide Fuel Cell (SOFC)

The solid oxide fuel cell (SOFC) operates in the region of 600 to 1000°C. This means that high reaction rates can be achieved without expensive catalysts, and that gases such as natural gas can he used directly, or'internally reformed' within the fuel cell, without the need for a separate unit. This fuel cell type addresses all the problems and takes full advantage of the inherent simplicity of the fuel cell concept. Nevertheless, the ceramic materials that these cells are made from are difficult to handle, so they are expensive to manufacture, and there is still quite a large amount of extra equipment needed to make a full fuel cell system. This extra plant includes air and fuel pre-heaters, also the cooling system is more complex, and they are not easy to start up Despite operating at temperatures of up to 1000°C, the SOFC always stays in the solid state.

Overview

The SOFC is a completely solid-state device that uses an oxide ion-conducting ceramic material as the electrolyte. It is therefore simpler in concept than all of the other fuel cell systems described as only two phases (gas and solid) are required. The electrolyte management issues that arise with the PAFC and MCFC do not occur and the high operating temperatures mean that precious metal electrocatalysts are not needed. As with the MCFC, both hydrogen and carbon monoxide can act as fuels in the SOFC. The SOFC is similar to the MCFC in that a negatively charged ion is transferred from the cathode through the electrolyte to the anode. Thus product water is formed at the anode. Until recently SOFCs have all been based on an electrolyte of zirconia stabilized with the addition of a small percentage of yttria (zirconia is zirconium oxide, yttria is yttrium oxide). Above a temperature of about 800°C, zirconia becomes a conductor of oxygen ions, and typically the state-of-the-art zirconia based SOFC operates between 800 and 1100°C.

This is the highest operating temperature of all fuel cells, which presents both challenges for the construction and durability, and also opportunities, for example in combined cycle (bottoming cycle) applications. The anode of the SOFC is usually a zirconia cermet (an intimate mixture of ceramic and metal). The metallic component is nickel, chosen amongst other things because of its high electronic conductivity and stability under chemically reducing and part-reducing conditions. The presence of nickel can be used to advantage as an internal reforming catalyst, and it is possible to carry out internal reforming in the SOFC directly on the anode. The material for the cathode has been something of a challenge. Most SOFC cathodes are now made from electronically conducting oxides or mixed electronically conducting and ion-conducting ceramics. The most common cathode material of the latter type is strontium-doped lanthanum manganite.

The high temperatures and presence of steam also means that CO producing hydrogen invariably occurs in practical systems, as with the MCFC. The use of the CO may thus be more indirect, but just as useful. Unlike the MCFC, the SOFC requires no CO recycling, which leads to system simplification.

However, one disadvantage of the SOFC compared with MCFC, is that the open circuit voltage of the SOFC at 1000°C is about 100 mV lower than the MCFC at 650°C. This could lead to lower efficiencies for the SOFC. However, in practice the effect is offset at least in part by the lower internal resistance of the SOFC and the use of thinner electrolytes. The result of this is that the SOFC can be operated at relatively high current densities (up to 1 A cm^{-2}).

The SOFC can be used in combined cycles, novel system designs and hybrid systems. The ability to use both gas turbines and steam turbines in a combined cycle with an SOFC has been known in concept for many years. However, it is only recently that pressurized operation of SOFC stacks has been demonstrated for prolonged periods, making the SOFC/gas turbine combined cycle system feasible practically. There are many opportunities for further novel system designs, and the scope for considerable creativity by the systems engineers. By using the concept of series stack connection mentioned first in connection with the MCFC, a "multi-stage" SOFC concept "UltraFuelCell" has been developed by the US Department of Energy. Perhaps one of the most novel ideas, is the hybrid or combined system concept described recently in which both SOFC and PEM fuel cells are combined. The advantages of each type of fuel cell are enhanced by operating in synergy. The use of two stacks of different types for power generation results in a high overall electrical efficiency. The system becomes particularly attractive if an economic analysis is carried out. Preliminary calculations show that the system is more cost effective than an SOFC-only system because of the anticipated relatively low cost of the PEM stack. On the other hand the system has a much higher efficiency than a natural gas fuelled PEM-only system could produce.

The tubular SOFC was pioneered by the US Westinghouse Electric Corporation (now Siemens-Westinghouse) in the late 1970s. Most recently the zirconia support tube has been eliminated from the design and the tubes are now made from air-electrode materials, resulting in an air-electrode-support (AES) onto which the electrolyte is deposited by EVD, followed by plasma spraying of the anode. One great advantage of the tubular design of SOFC is that high temperature gas-tight seals are eliminated. By allowing imperfect sealing around the tubes, some recirculation of anode product gas occurs allowing internal reforming of fuel gas on the SOFC anode.

Alternatives to the tubular SOFC have been developed for several years, notably several types of planar configuration, and a monolithic design. The planar configurations more closely resemble the stacking arrangements described for the PAFC and PEMFC. This bipolar or flat plate structure enables a simple series electrical connection between cells without the long current path through the tubular cell. The bipolar flat plate design results in lower ohmic losses, superior stack performance and a much higher power density. Another advantage of the planar design is that low-cost fabrication methods such as screen-printing and tape casting can be used.

One major disadvantage of the planar design is the need for gas-tight sealing around the edge of the cell components. Using compressive seals this is difficult to achieve and glass ceramics have been developed in an attempt to improve high temperature sealing. Similarly, thermal stresses at the interfaces between the different cell and stack materials tends to cause mechanical degradation, so thermal robustness is important. Particularly challenging is the brittleness of planar SOFCs in tension. Thermal cycling is also a problem for the planar SOFC. Finally, the issue of thermal stresses and fabrication of very thin components places a major constraint on the scale up of planar SOFCs. Until recently, planar SOFCs could be manufactured only in sizes up to 5 x 5 cm. Now 10 x 10 cm planar cells are routinely made.

As mentioned earlier, with hydrogen as the fuel, the open circuit voltage of SOFCs is lower than that of MCFCs and PAFCs. However, the higher operating temperature of SOFCs reduces polarization at the cathode. So, the voltage losses in SOFCs are governed mainly by ohmic losses in the cell components, including those associated with current collection.

SOFC is very similar to a molten carbonate fuel cell except it can scale down more effectively and the use of exotic materials has improved temperature cycling capability. The electrolyte is an ion conducting oxide ceramic that allows the oxygen ion to pass through to the anode, combine with the hydrogen to form water and heat.

There are several types of planar Solid Oxide Fuel Cells (SOFCs) that are being developed. The conventional system has been the 'Electrolyte Supported' concept. This design has a thick electrolyte with thin anode and cathode layers. This was the first type of system developed and is still used by many companies today.

These systems require very high operating temperatures ranging from 900 to 1100°C. The main disadvantage of this design is that high operating temperatures require specialized and exotic materials for interconnect and other stack components. This leads to high material and production costs. These high temperatures also present a problem for long term operation and reliability due to material oxidation problems as well as integrating the required balance of plant.

A newer and more innovative 'Anode Supported' cell concept is being developed, which has a thick anode that acts as the supporting structure and the electrolyte and cathode are very thin in comparison. This type of cell generally operates within a temperature range of 750 to 850°C. the anode; cathode and electrolyte are made from ceramic materials to withstand the temperatures. The ceramic cell is then 'sandwiched' or held between metal interconnecting plates that act as air and gas flow plates as well as the electrical connection between each cell. At these mid range temperatures, lower cost exotic material can be used. Within this

temperature range, long term operation is much improved although there may still be some longer-term degradation due to oxidation of the metallic interconnects.
In order to produce significant amounts of power, solid oxide fuel cell elements are assembled into a stack, analogous to a multi-layered sandwich. Cell membrane assemblies, each including an anode, electrolyte, and cathode are stacked with metal interconnecting plates between them. The metal plates, made of standard stainless steels are shaped to allow flow of the hydrogen and oxygen to the membranes.

It is important to put the high operating temperature of the SOFC in perspective. These are very common temperatures in many applications. As an example, the flame temperature in the combustion chamber in an automobile is in the range of 2300 °C. The gas temperatures entering the exhaust manifolds in an automobile range from 700 to 1100 °C. The SOFC typically uses an insulating shell to maintain the high temperature and air, rather than water for cooling. The outside temperature of the SOFC is typically 40 to 50 °C. The concern of an explosion from fuel cells is unwarranted and the risk is no greater than your present internal combustion (IC) engine. When operating and reforming fuels such as gasoline, the fuel storage and overall reaction is the same as with the internal combustion engine (although at a much higher efficiency). The fuel is reformed to produce gases such as hydrogen and carbon monoxide. However, these constituents exist only in small quantities and are consumed soon after production. The fuel cell stack has a small mass compared to that of the IC engine. Thus, it will cool just as fast if not faster than an IC engine in the event that the heat shroud is damaged in an accident.

3.1.5 Proton Exchange Membrane Fuel Cell (PEMFC)

The PEM fuel cell capitalizes on the essential simplicity of the fuel cell. The electrolyte is a solid polymer, in which protons are mobile. The chemistry is the same as the acid electrolyte fuel cell. With a solid and immobile electrolyte, this type of cell is inherently very simple. These cells run at quite low temperatures, so the problem of slow reaction rates is addressed by using sophisticated catalysts and electrodes. Platinum is the catalyst, but developments in recent years mean that only minute amounts are used, and the cost of the platinum is a small part of the total price of a PEM fuel cell. The problem of hydrogen supply is not really addressed - quite pure hydrogen must be used, though various ways of supplying this are possible.
The electrochemical reaction occurs at 80-110°C and thus the PEMFC does not require much exotic material other than the membrane electrode assembly (MEA) and flow plates. The MEA typically consists of a solid polymer sheet embedded with catalyst that facilitates the hydrogen and oxygen electrochemical reaction to produce water and electricity. The MEA also acts as electrical insulator between the positive (+) and negative (-) electrodes and separator to prevent water from flowing back into the anode plate. PEMFC can also be designed to provide both generative and regenerative modes. When in generative mode, PEMFC can produce electrical power instantly when fed with pure hydrogen and oxidant after a few minutes of warm up time. When in regenerative mode the PEMFC functions like an electrolyzer and produces hydrogen and oxygen when fed with electricity and water. The dual mode capability is very attractive for standby power and remote hydrogen generation applications.

Overview
The proton exchange membrane fuel cell (PEMFC), also called the "solid polymer fuel cell" (SPFC), was first developed by General Electric in the USA in the 1960's for use by NASA on their first manned space vehicles. The electrolyte is an ion conduction polymer. Onto each

side is bonded a catalyzed porous electrode. The anode-electrolyte-cathode assembly is thus one item, and is very thin. These "membrane electrode assemblies" (or MEAs) are connected in series, usually using bipolar plates.

The mobile ion in the polymers used is an H$^+$ ion or proton, so the basic operation of the cell is essentially the same as for the acid electrolyte fuel cell. The polymer electrolytes work at low temperature, which brings the further advantage that a PEMFC can start quickly. The thinness of the MEAs means that compact fuel cells can be made. Further advantages are that there are no corrosive fluid hazards, and that the cell can work in any orientation. This means that the PEMFC is particularly suitable for use in vehicles and in portable applications.

The development of PEM cells went more or less into abeyance in the 1970's and early1980's. However, in the latter half of the 1980's and early 1990's there was a renaissance of interest in this type of cell (Prater, 1990). A good deal of the credit for this must go to Ballard Power Systems of Vancouver, Canada and to the Los Alamos National Laboratory in the USA.

The developments over recent years have brought the current densities up to around 1-2 A/cm^2 or more, while at the same time reducing the use of platinum by a factor of over 100. These improvements have led to huge reduction in cost per kW of power, and much improved power density. A sign of the dominance of this type of cell is that they are again the preferred option for NASA, and the new Space Shuttle Orbiter will use PEM cells. It could be argued that PEMFCs exceed all other electrical energy generating technologies in the breadth of scope of their possible applications. They are a possible power source at a few watts for powering mobile phones and other electronic equipment such as computers, right through to a few kW for boats and domestic systems, to tens of kW for cars, to hundreds of kW for buses and industrial CHP systems. Within this huge range of applications two aspects of PEM fuel cells are more or less similar. These are the electrolyte used and the electrode structure and catalyst.

Other important aspects of fuel cell design vary greatly depending on the application and the outlook of the designer. The most important of these are: water management, the method of cooling the fuel cell, and the method of connecting cells in series. The bipolar plate designs vary greatly, and some fuel cells use altogether different methods. The reactants used are also an important issue - pure hydrogen is not the only possible fuel, and oxygen can be used instead of air. There are, of course, other important questions, such as "where does the hydrogen come from?" but these questions are large, and apply to all fuel cell types.

The different companies producing polymer electrolyte membranes have their own special tricks, mostly proprietary. However, a common theme is the use of sulphonated fluoro-polymers, usually fluoroethylene. The most well known and well established of these is Nafion (reg. Dupont), which has been developed through several variants since the 1960's. This material is still the electrolyte against which others are judged, and is in a sense an "industry standard". Other polymer electrolytes function in a similar way. The modified polymer, is polytetrafluoroethylene, or PTFE. It is also sold as Teflon, the registered trademark of ICI. This remarkable material has been very important in the development of fuel cells.

It will be very rare for a designer to have a real choice between the use of air or oxygen in a PEM fuel cell system. Oxygen is used in air independent systems such as submarines and spacecraft. Otherwise, air is used for other PEM fuel cell systems. However, the use of oxygen does markedly improve the performance of a PEM fuel cell. This results from three effects:

- The "no loss" open circuit voltage rises due to the increase in the oxygen partial pressure,
- The activation overvoltage reduces, due to better use of catalyst sites,

- The limiting current increases, thus reducing the mass transport or concentration overvoltage losses. This is because of the removal of the nitrogen gas, which is a major contributor to this type of loss at high current densities.

3.1.6 Direct Methanol Fuel Cells (DMFC) and other liquid fuels

Direct (oxidation) methanol fuel cells (DMFC) are attractive for several applications in view of their lower weight and volume compared with indirect fuel cells. In this kind of fuel cell, solid polymers have been shown as an attractive alternative to the traditional liquid electrolytes. Nafion perfluorosulfonic acid polymers are the most commonly used fuel cell membranes. Although it would be desirable that methanol could be spontaneously oxidized at the cathode, methanol transport across the membrane has been observed. It causes depolarization losses at the cathode and conversion losses in terms of lost fuel. In order to improve the performance of the DMFC, it is necessary to eliminate or, at least, to reduce the loss of fuel across the cell, usually termed "methanol crossover". In this sense, the membrane technology is one of the alternatives for trying to solve this problem.

An ideal fuel for any fuel cell would be a liquid fuel already in regular use, such as gasoline (diesel) petrol. Unfortunately such fuels simply do not react at a sufficient rate to warrant consideration at the present time - with the exception of methanol. Methanol is already used as a fuel in some vehicles (e.g. certain types of racing car), and is readily available. It is used, for example, at the staggering rate of 250 million US gallons a year as a cleaner/solvent for automobile windshields. Methanol reacts at the anode of a PEM fuel cell by the equation:

$$CH_3OH + H_2O \rightarrow 6H^+ + 6e^- + CO_2$$

Note that the methanol needs to be mixed with water, and that six electrons are produced for each methanol molecule. Such fuel cells are called "direct methanol" fuel cells. This is in contrast to a fuel cell that uses hydrogen produced from methanol in a reformer, which could be called an "indirect methanol" fuel cell. The most pressing problem with the direct methanol fuel cell is that the rate of reaction is very slow. This manifests itself as a high activation over-voltage on the anode. The result is a very low operating voltage, and thus a very low efficiency. The problem of fuel crossover is also much worse than with hydrogen, as the methanol is absorbed into the polymer electrolyte. Despite these problems, the easy availability, ease of storage and handling, high energy density and safety of methanol fuel make it so attractive that certain low power applications seem certain to appear soon. A good example might be a unit for recharging portable telephones. A direct methanol fuel cell could be incorporated into the holder of a cell phone, and keep it charged up while on standby. It has been calculated that such a unit would only have to have an efficiency of 4% to make it compete with battery technologies such as lithium for longer mission duration.

Storage in liquid form is an important advantage of methanol vs. hydrogen for portable power source applications. The effective energy density of methanol, assuming DMFC cell voltage of 0.5 V (a typical design point) and 90% fuel efficiency, is 2.25 kW h/kg. In comparison, for hydrogen stored as metal hydride at 2% by weight and assuming hydrogen/air cell voltage of 0.7 V, the effective energy density of the fuel is 0.4 kW h/kg. The power densities of a hydrogen/air PEFC and of a DNWC are not highly different when both operate near ambient conditions, leaving the DMFC system with the advantage of significantly denser form of (liquid) fuel storage. The DMFC reduces the system complexity considerably. Furthermore, the DMFC enables a quick start-up procedure, because there are no units which have to be heated to several hundred degrees centigrade as has to be done in a fuel processor. Additionally, an emission of carbon monoxide could be completely avoided in case of the DMFC, while the catalytic burner of a PEMFC + reformer system produces small amounts of

CO, which are released in the exhaust gas. The main disadvantage of the DMFC system is the relatively low power density, which has to be significantly improved if the DMFC should be a viable alternative to the PEMFC plus reformer system.

The lower cell performance of a DMFC is caused by the poor kinetics of the anode reaction. Methanol is oxidized to carbon dioxide at the anode of a DMFC. But the oxidation reaction proceeds through the formation of carbon monoxide as an intermediate, which strongly adsorbs on the surface of a Pt catalyst. Therefore, a potential, which is much more anodic than the thermodynamic value, is needed to obtain a reasonable reaction rate. in contrast to the PEMFC, where it is mainly the cathode that is kinetically hindered, both electrodes of a DMFC suffer from kinetic losses.

At present, the most active catalysts are based on Pt-Ru alloys. Ruthenium reduces the poisoning effect by lowering the overpotentials at the anode and thus increases considerably the catalytic activity of pure platinum. Moreover, the commercially available polymer electrolyte membranes, which are used for the assemblies, are not optimized for the use in a DMFC. Methanol can permeate through the membranes from the anode to the cathode and interact with the latter electrode. Therefore, the cathode potential is decreased and a loss of the cell voltage occurs. Furthermore, the diffusion of methanol to the cathode leads to a loss of fuel and thus to a diminished efficiency.

3.2 Technology Trends

3.2.1 Alkaline Fuel Cells

This technology is adequately developed for the space application but has relatively higher capital costs compared to other fuel cell technologies. Further development is required to reduce capital cost, improve thermal cycling, terrestrial environmental conditions and user friendliness. The Alkaline Fuel Cell can not operate with carbon dioxide in either the fuel or oxidant. Even the small amount of carbon dioxide in the air is harmful. Therefore, this type of fuel cell is generally limited to applications where pure hydrogen and oxygen are available. The corrosive alkaline electrolyte is still a threat to the user and its surrounding equipment if it ruptures. The major advantages of alkaline electrolyte fuel cells are that the activation overvoltage at the cathode is generally less than with an acid electrolyte. Also, the electrodes can be made from non-precious metal electrodes, and no particularly exotic materials are needed. The electrolyte needs to be an alkaline solution, with sodium hydroxide and potassium hydroxide solution, being the lowest cost. It turns out that potassium carbonate is much more soluble than sodium carbonate, this is an important advantage.

3.2.2 Phosphoric Acid Fuel Cells

The PAFC requires exotic material and innovative design to reduce corrosion and improve sensor reliability, thus has a relatively higher capital cost. It has now reached a level of maturity where developers and users are focusing their resources to producing commercial capacity, multi-unit demonstrations and pre-prototype installations. Cell components are being manufactured at scale and in large quantities. However, the technology is still too costly to be economic compared with alternative power generations systems, except perhaps in niche premium power applications. There is a need to increase the power density of the cells and reduce costs, both of which are inextricably linked. System optimization is also a key issue. As well, catalyst development is still an important aspect of the PAFC. Other recent significant developments in PAFC technology are improvements in gas diffusion electrode construction, and tests on materials that offer better carbon corrosion protection. Of course many improvements can be made in the system design, with better balance-of-plant components such as the reformer, shift reactors, heat exchangers, and burners.

Since the PAFC can operate on lower quality hydrogen fuel with a relatively higher overall efficiency, this technology can become cost effective to some civilian and military applications. Until recently the PAFC was the only fuel cell technology that could be said to be available commercially. Systems are now available that meet market specifications, and they are supplied with guarantees. Many of these systems have now run for several years, and so there is a wealth of operating experience from which developers and end users can draw.

The Phosphoric Acid Fuel Cell has been under development for 15 years as an electric powerplant. While it has a lower real efficiency than the MCFC or SOFC, the lower operating temperature of 160-220°C was considered more ideal for small and midsize powerplants. Midsize 200 kW AC powerplants are 40% efficient and large 11MW units are 45% efficient when running on natural gas. These efficiencies are comparable to the PEMFC.

3.2.3 Molten Carbonate Fuel Cell

There are no materials available that are stable enough for use at MCFC temperatures that are comparable to PTFE. Thus, a different approach is needed to establish a stable electrolyte/gas interface in MCFC porous electrodes. The extreme high operating temperature and molten electrolyte contains potential safety hazards to the personnel and equipment in the nearby vicinity. It also create challenges on material and sensors applications, thermal cycling capability and system reliability.

This technology is more suitable for continuous operation for stationary land-based requirements and has limited opportunities for tactical use. The Molten Carbonate Fuel Cell has also been under development for 15 years as an electric powerplant. The operating temperature of 600-650°C is lower than the SOFC. It is considerably more efficient that the PAFC. It already has the advantage of reforming inside the stack. It's disadvantage is the corrosiveness of the molten carbonate electrolyte. Large AC powerplants using gas turbine bottoming cycles to extract the waste heat from the stack could be up to 60% efficient when operating on natural gas. When problems with the SOFC are solved, work on the MCFC may be disbanded. Therefore no DND R&D investment needed because of its very limited military application.

3.2.4 Solid Oxide Fuel Cell

A significant advantage of the SOFC is that it does not need an external reformer or 'mini-refinery' to make hydrogen. Instead, due to the higher operating temperature, hydrogen is produced directly through a catalytic reforming process either directly inside the cell or external to the cell in the hot zone. Carbon monoxide, a contaminant in the PEM systems is a fuel for the SOFC. This direct reforming allows the SOFCs to utilize natural gas, propane, and other hydrogen rich fuel where available.

Since SOFCs are traditionally used by utilities, remote communities and the petroleum industry as stand alone installations for prime power, they have not been designed for thermal cycling and a glass seal is generally used around the cells as well as the gas manifolds. When the unit is thermally cycled, as required in mobile application, the glass seals crack and form leakage paths, allowing the stack to deteriorate.

SOFC is an extremely efficient overall system with fuel efficiency of 60%. Combined power conversion and waste heat recovery total system efficiencies of over 80% are attainable. Many stationary applications can use the waste heat for space and process heating. The SOFC can also be designed and manufactured for mobile application once vibration, temperature cycling and safety issues have been adequately addressed.

There is a very strong Canadian niche in this technology within industry and OGD (such as NRC and NRCan (IEA & PERD)). Defence Engineering and Research Agency (DERA) of UK is developing a new fuel cell technology that offers the same performance as the SOFC but at temperatures of 350 -500°C. This will reduce the requirement for specialty material, sensors and sophisticated fabrication. Technology Management Inc (TMI) of US has developed and demonstrated a low power, compact portable, and sulfur tolerant SOFC that can utilize various type of fuel, such as JP8, natural gas, and other common fuels. TMI's SOFC operates in the region of 950°C, utilizing an integrated stack and a high temperature catalyst fuel reformer. Continuing efforts focus on thermal cycling, cell life and efficiency. Siemens-Westinghouse and several other organizations, notably Mitsubishi Heavy Industries in Japan and also the group at Keele University in the UK, have been developing tubular SOFC designs. Nevertheless, the Siemens Westinghouse design is the most advanced.

Global Thermoelectric Inc of Canada is developing a newer and more innovative 'Anode Supported' cell concept. At present, their design is expected to surpass the industry goal of 1 kilowatt per liter, and continues to strive to produce the smallest unit for a given power size. They have been performing R&D on high temperature compressive gaskets and this past year announced that a new high temperature compressive gasket had been developed. The new seal provides three significant advantages. First, the stack can now be thermally cycled without degradation or leakage. Second, the unit should be able to undergo vibration and shock that was not possible with glass sealing. Third, with the use of compressive sealing, the stacks can be heated and cooled much faster because the components can expand and contract accordingly.

Canadian governments, in a joint venture with US Department of Energy and Siemens Westinghouse Power Corp, are investing $18M to build the world's largest prototype solid oxide fuel cell heat and power co-generation demonstration plant in Toronto, at Ontario Power Generation Inc. Many other US and Canadian companies are involved as well.

3.2.5 Proton Exchange Membrane Fuel Cell

Cold weather operations pose severe challenges to the PEMFC. But, internal combustion engines performances poorly under cold weather as well. Typical PEMFC is also not suitable for extreme cold temperatures if it is not purposely designed to operate in such an environment. Since PEMFC operates at 80-100°C, and its byproduct is water, thus this water can freeze when subjected to ambient below 0°C. The problem arises when the cold ambient dissipates byproduct heat quicker than the chemical process produces, or when the fuel cell is deactivated (in OFF condition). Typical MEA in the PEMFC needs humidity to prevent it from getting brittle and to improve load responds. However, allowing the byproduct water and moisture to freeze in an uncontrolled manner can damage the MEA, the stack, and the fuel system. Tactical PEMFC must be designed to meet wide ranges of environmental conditions and temperature is a critical parameter.

The PEM can be poisoned if either the hydrogen or oxidant contains contaminant that the MEA can not tolerate. As a result the hydrogen fuel and oxidant must be relatively pure and thus imposes a stringent requirement on fuel processing, storage, and oxidant scraping. Under tactical environment the emerging electrochemical or electrolysis processes can potentially produce purer hydrogen, and new fuel storage devices are more contamination free. It is a challenge to filter out contaminants since the battlefield could contain smoke, diesel exhaust, explosive and munitions flumes, chemical agents and gases, etc. With further development and design, future PEMFC can be hardened against these types of contaminants.

There are many parameters of PEM fuel cells that can be changed. These changes, such as operating temperature and pressure, air stoichiometry, reactant humidity, water retaining properties of the gas diffusion membrane, and so on, affect the performance of the cell in fairly predictable ways. This naturally lends itself very well to the construction of computer models. This can be done for things as specific as the water and heat movement. Alternatively the performance of a single cell under different conditions can be modeled. Work on Pt and other catalysts, to lower the amount of expensive catalysts or to eliminate them, is necessary in order for PEM to replace other traditional power sources in the military by 2020. R&D needed on new lightweight materials and catalysts will be needed to make the PEM fuel cell suitable for the military.

3.2.6 Direct Methanol Fuel Cells

During recent years large efforts were made to develop improved catalysts, to optimize the electrode structure and to improve the fuel cell design. This has led to a rapid improvement of the performance of the DMFC so that at a cell voltage of 0.5 V power densities can be achieved in the range of 200-340 mW/cm^2 for the pure oxygen mode and 150-180 mW/cm^2 for air-operated cells. But a comparison of data from different groups is difficult. Experimental parameters, which have a strong impact on the cell performance (such as temperature, pressure, noble metal loading, oxygen excess), differ greatly.
Several companies around the world are presently working on DMFC. Even in 1999 there has been a marked shift away from developing the PEFC in favor of the DMFC. The operating temperature of 50-100°C is low and so is ideal for tiny to midsize applications. The electrolyte is a thin polymer similar to the PEFC. This type of fuel cell was largely overlooked in the early 1990s because the efficiency was below 25%. There has been tremendous progress made in the last 6 years. Efficiencies of the DMFC are much higher and predicted efficiencies in the future may be as high as 40% for a DC automobile powerplant. Power densities are over 20 times as high now as in the early 1990s. It is expected that the DMFC will be more efficient than the PEMFC for automobiles that use methanol as fuel. Recent R&D efforts devoted to direct methanol fuel cells (DMFC) have targeted potential applications ranging from portable power for consumer electronics to transportation. Los Alamos has been involved in DMFC R&D projects addressing potential applications covering this wide range. One central DMFC project at Los Alamos National Laboratory (LANL), funded by the Defense Advanced Research Project Agency (DARPA), has been devoted to portable power applications. The other has been devoted to potential transport applications and supported by the US DOE. Significant differences between technical parameters and targets for the two different DMFC applications include the lower cell temperature (60°C or below) and ambient air pressure preferred in portable power vs. operation around 100°C as target temperature, with possible use of pressurized air, for transport applications. Also, a much stronger concern for cost of catalyst and other stack materials and components arises in the context of DMFCs developed for potential transport applications. Most, if not all recent DMFC work for either portable power or potential transport applications, has strongly focused on cells with polymeric, primarily perfluorocarbon sulfonic acid (PFSA) membrane electrolytes. Recently, the machined graphite hardware has been replaced by alternative, non-machined flow-field/bi-polar plate hardware, which enables effective air and aqueous methanol solution distribution along the cell active area at reduced cell width of just 2 mm.

The problems that remain to be solved are:
(1) to find electrocatalysts that would (a) enhance the electrode kinetics of methanol oxidation, and (b) minimize the poisoning caused by strong adsorption of CO-type intermediates,
(2) find electrocatalysts for oxygen reduction which are not depolarized by the methanol crossover from the anode to the cathode via the membrane by optimizing the structure of

the electrodes and the operating conditions or by ending membranes which inhibit the methanol transport, and
(3) the engineering design and construction of the electrochemical multi-stack.

Other Fuels
Solid oxide fuel cells can also use hydrocarbon fuel directly to generate energy, but to date this mode of operation resulted in either carbon deposition at high temperatures or poor power output at low operating temperatures. It is however possible to use direct electrochemical oxidation of methane in solid oxide fuel cells. Current research is estimating that it is possible to generate power densities up to 0.37 W cm^{-2} at 650 °C, which is comparable to that of fuel cells using hydrogen. This can be achieved by using ceria-containing anodes and low operating temperatures to avoid carbon deposition. By furthering R&D into the incorporation of more advanced cathodes the performance of the SOFC would improve, making the solid oxide fuel cell a promising candidate for practical and efficient fuel-cell applications.
The direct electrochemical oxidation of hydrocarbon fuels in SOFCs is, in principle, possible. However, to date, it has resulted in carbon deposition at operating temperatures above about 800 °C, and low power densities (10 mW cm-2) at temperatures below 800 °C. But recently developed SOFCs that produce high power densities by using hydrogen fuel at 600–800 °C may have the potential to provide good power densities by directly using hydrocarbons in a temperature range where carbon deposition can be avoided. A significant amount of R&D needs to be done to overcome many problems in the development of a methane SOFC stack, but is a viable and attractive method of power generation for military purposes and fully functional prototypes could be ready for demonstration in 2020.

3.2.7 General Trend

Problems have plagued the introduction of fuel cells to date. Fuel cells are still several years away from commercialization on a large scale. It is very difficult to tell which fuel and which technology will be predominant in the future. There are some problems to be solved in the SOFC and the DMFC. If these can be solved then these will become the predominant fuel cells being developed in the future. In the last year there has been considerable progress made in this direction. Ballard has purchased the DMFC technology from JPL, and Global has made big progress towards commercializing the SOFC technology.
Present and future material science development may make them a reality soon (2010) in specialized applications for the military. The Solid Oxide Fuel Cell appears to be the most promising technology for small electric powerplants over 1 kW. The Direct Methanol Fuel Cell appears to be the most promising as a battery replacement for portable applications such cellular phones and laptop computers. The Proton Exchange Membrane Fuel Cell has the potential to be used in a wide range of applications, if hydrogen storage issues can be resolved.
It is difficult to tell at this moment which fuel cell will be most practical for transportation applications such as automobiles and buses. Fuel cells used as electric powerplants may be successful before vehicular ones are. This is because a fuel cell produces electric power which is what is required in this case. In transportation applications the electricity produced must then be converted to mechanical power. It is unclear whether we will move to a hydrogen economy. This is because solid oxide fuel cells may be widely used and these can cleanly convert renewable hydrocarbon fuels. Fuel cells are analyzed theoretically using the Carnot-ratio which applies to both heat engines as well as fuel cells. A simple second-law analysis shows where the loss of efficiency in different fuel cells occurs.

Various types of fuel cells can be developed and packaged to meet specific design parameters and applications. However, due to processing temperature and balance of plant, certain types of fuel cells will be more suitable than others for military applications due to capital cost, user friendliness, efficiency, reliability, size, weight and volume, logistic and maintenance supports. Table 12 lists the fuel cells and their potential applications, but new emerging fuel processing techniques and new materials will influence this list in 2020 as explained above. Batteries have limited ampere-hour capacity and fuel cells offer the potential of being more rapidly refueled with hydrogen cartridges or hydrogen derivatives and significantly more environmentally friendlier than ICE & gas turbines. A fuel cell generates less pollution and should be able to be hardened to withstand hostile battlefield environment and manufactured in form, fit and function to meet tactical performance requirements with further R&D. Fuel cell technology can potentially replace internal combustion engines, gas turbines and batteries in many military applications because of their better performance characteristics compared with current electrical power sources.

Table 12: Military Application Fuel Cell Technology

Fuel Cell Applications	**AFC**	**PAFC**	**MCFC**	**SOFC**	**PEMFC**	**DMFC**
Micro-chip < 10g					√	√
Hand held devices < 500g					√	√
Portable devices < 10 kg				√	√	√
Personnel luggable device < 100kg	√			√	√	√
Chassis mounted device < 1000kg	√	√	√	√	√	√
Transportable container or shipboard mounted device < 10,000kg	√	√	√	√	√	√
Land based power plant > 10,000kg	√	√	√	√	√	√

The provision of suitable fuels is an essential problem for the technical and economical application of fuel cells. The hydrogen PEM fuel cells are supplied with gaseous hydrogen. But there is no infrastructure established yet for the distribution and storage of hydrogen, neither as a liquid nor as a gas. Another possibility could be the on-board generation of hydrogen from a liquid fuel by a fuel processor, comprising a reformer, a catalytic burner and a CO removal unit. The hydrogen rich gas, produced by this fuel processor, is then supplied to the anode of the PEM fuel cell. Methanol is a possible candidate as a liquid fuel due to its high energy density. It would enable simple and safe handling and a low cost distribution system.

3.3 Research and Development Opportunities

3.3.1 Alkaline Fuel Cell (AFC)

The success of PEM fuel cell developments in recent years has furthered the decline in interest in alkaline fuel cells, and now very few companies or research groups are working in the field. There is no major Canadian R&D activity in this fuel cell technology and some R&D is being conducted by others internationally. Information can be obtained from OGD participating in the International Energy Agency annex on Fuel cells. No DND R&D activity is warranted in the next ten year cycle. The alkaline fuel cell has potential military applications for portable and transportable power generators, and also as propulsion prime power.

3.3.2 Phosphoric Acid Fuel Cell (PAFC)

As with the AFC, there is no major Canadian R&D activity in this fuel cell technology and some R&D is being conducted by others internationally. Information can be obtained from OGD participating in the International Energy Agency annex on Fuel cells. Thus, no DND R&D activity is warranted in the next ten year cycle.

3.3.3 Molten Carbonate Fuel Cell (MCFC)

This technology is more suitable for continuous operation for stationary land base requirements and has limited opportunities for tactical use. It has also been under development for 15 years as an electric powerplant. The operating temperature of 600-650°C is lower than the SOFC. It is considerably more efficient than the PAFC. It already has the advantage of reforming inside the stack. It's disadvantage is the corrosiveness of the molten carbonate electrolyte. Large AC powerplants using gas turbine bottoming cycles to extract the waste heat from the stack could be up to 60% efficient when operating on natural gas. When problems with the SOFC are solved, work on the MCFC may be disbanded. No DND investment is warranted as it has very limited military application.

3.3.4 Solid Oxide Fuel Cell (SOFC)

The military requirements for low temperature operation and high power output generators means further R&D into SOFC will provide useable units in 2010-2020 timeframe only with direct DND R&D investment into the technology. The industry currently investing in this area is more interested in exploiting the technology for large, more cost effective units for electricity generation. The development and use of materials that are more robust for military use, the wide temperature requirements that the military uses its power sources in, as well the need for system designs and improved materials for smaller/portable applications will not be invested into by industry by themselves. DRDC can stimulate investigation into this area by working with OGD and industry on several beneficial topics. Money can be effectively leveraged with OGD and industry because of the activity already going on in Canada. Therefore, DRDC can support development of SOFC units for DND applications with leveraged activities of 1:3 cost sharing with its partners. Because the use of SOFCs is expected to be dominant, compared with other fuel cells (excepting direct and indirect PEM fuel cells), DRDC should have one half PY working in the area of fuel cell technology.

The direct topics DRDC should address in this technology are:

1) The direct electrochemical oxidation of hydrocarbon fuels in SOFCs
2) Improvement in materials for both smaller design and cold temperature operation

Among the various high temperature fuel cell technologies, including AFC, MCFC and PAFC, the SOFC is the most fuel tolerant power source for military applications above 10kW capacity, such as power generation and propulsion applications. It is a suitable central power source for command post, field hospital and camp, vehicular and shipboard hotel and propulsion, direct beam weapon and electric fused munitions, and North Warning Stations. Because of anticipated future industrial and OGD efforts, strong leveraging of DND resources is expected and military specific units could be developed at 1/3 the cost. Demonstration units could be available as early as 2010. It is estimated one half PY within DND to support R&D into SOFC.

3.3.5 Proton Exchange Membrane Fuel Cell (PEMFC)

The Proton Exchange Membrane Fuel Cell has the potential to be used in a wide range of applications, if hydrogen storage issues can be resolved. Research on the fuel cell stack itself is still progressing slowly with most of research being done by industry and academia with little direct DRDC investment required except in the following areas:

1) Development of better catalysts to lower risk of fuel cell exposure to battlefield contaminants which could poison the fuel cell.
2) Improved hydrogen storage issues that directly impact on the military use of fuel cells.
3) Improved performance parameters for military specific applications such as high powered soldier systems anticipated in 2020.

This would require about one half a PY from DND to manage leveraged projects with Canadian industry, RMC and government partners such as NRCan and NRC which share common interests in the technology.

3.3.6 Direct Methanol Fuel Cells (DMFC) and other liquid fuels

Direct Methanol Fuel Cells appear to be the most promising as battery replacements for portable applications such as cellular phones and laptop computers. Because of the anticipated direct industrial investment many technological issues will be solved by industry. However, DRDC investment will be needed in several topics to exploit this system for military equipment:

1) Exploring use of logistic fuels (diesel) in direct fuel for fuel cells
2) Improved efficiency and materials for low temperature operation of DMFC (if they are to replace military batteries down to – 40 °C)
3) Find electrocatalysts that would enhance the electrode kinetics, minimize the poisoning, optimize the structure of the electrodes and the operating conditions, and improve design and construction of the electrochemical multi-stack.

This would require about one half a PY from DND to manage leveraged projects with Canadian industry, RMC and government partners such as NRCan and NRC which share common interests in the technology.

Overall requirement is about two full-time PYs in DRDC doing in-house R&D and management of 2-3 leveraged projects with industry, OGD and university.

3.4 Air Filters for Fuel Cells and Weapon Platforms

Battlespace is a very harsh environment on personnel and their equipment. Other than typical environmental factors such as shock, vibration, temperature extremes, dusts, and exposures, advanced power sources will also be subjected to new threats resulting from the proliferation of battlefield contaminants. Battlefield contaminants include, but not limited to, engine exhausts, weapon discharges, smoke munitions, chemical warfare agents, high-energy waves, and explosives etc.

Combat conditions also require the soldiers and their equipment to maneuver in dusty, and muddy locations, diving into flooded trenches or swimming in water, or operating in areas contaminated with biological and chemical agents, or smoke and flares munitions. Since most of the fuel cells extract oxygen from the atmosphere as part of their fuel, thus the quality of oxygen and quantity of harmful chemicals in the air are critical to their performance. DERA UK [1] has examined the effects of various battlespace air pollutants and chemical warfare agents with results indicating some chemicals can degrade the fuel cells power output whereas other chemicals can totally destroy their functionality.

It is envisaged that for effective operation under extreme weather conditions or in a contaminated environment, fuel cells will be integrated into the soldier's environmental (uniform) clothing. For extreme cold weather operations, the fuel cells can be located inside the parka where the body heat can prevent the freezing of the fuel cell membrane. When operating under extreme hot condition, the fuel cells can be located exterior to the clothing but extracting the process air from inside the clothing, which then can help to cool a soldier by increasing air flow inside the uniform. To facilitate such an adaptation, compact and flexible air filters will be required for the environmental clothing to filter out exterior air prior to entering the body-suit citadel. As ships, submarines, jet fighters, UAVs, vehicles, weapons and all other chassises that will become the host to fuel cell power sources, advanced air filters will also be required to create a clean air citadel both for the fuel cells and personnel.

Since fuel cells will be deployed to power many critical sensors, equipment and weapons, ill-deployed fuel cells will risk life and jeopardize operations. Commercial-off-the-shelf (COTS) air filter products will not meet the battlespace survivability requirements. To ensure that the power sources and the soldiers are deployable and survivable in harsh and contaminated battlespace environments, advanced air filter technologies with high airflow, efficient filtering and low power consumption will be required. These filter media will also be required to operate effectively under extreme temperatures, under dry or flooded conditions, in clean and contaminated environments, under shocks and vibrations, high electromagnetic and blast waves.

3.4.1 State-of-the-Art

Pressure swing adsorption (PSA) is a reversible chemical process in which certain types of zeolites catalyst, when chemically treated, adsorb a selective range of gaseous molecules under slight pressure and release the molecules when the pressure is reduced. The technology is widely used in industrial gas purification, personal medical oxygen supply and aboard military aircraft for oxygen and nitrogen generation. More recently, specially developed zeolites in smaller PSA units have been developed which remove a range of battlefield gases and vapors to provide safe breathing air for pilots of low flying, ground attack helicopters. Similar devices could be used on mobile command vehicles and troop transports for cleanup of breathing air. The principal limitation to wide spread use at this time is the overall size of the unit and the need for relatively high-pressure compressed air, or electric power, to operate the units.

3.4.2 Technology Trends

Air filters are primarily developed for commercial application such as industrial pollution prevention and oxygen enrichment for combustion processes. Air filters for gas masks, aircraft and ship citadels have been developed for military but the technology is bulky low cycle life, and energy intensive. The current trends indicate that there will be significant technology gaps in meeting the following requirements:

a) *Smart Air Filters*

- advanced pressure swing adsorption catalytic system
- rejuvenatable/recyclable filter media
- high air volume, low pressure, low energy and compact filters floodable filter media

b) *Flexible Fabric Type Air Filter*

- new membrane material
- high air volume, low pressure, no power and compact filters
- nano-technology
- washable and floodable

c) *Air Filter Media Rejuvenator*

- portable, compact, low power and high feed-through rate
- weapon platform type media rejuvenator

3.4.3 Research and Development Opportunities

QuestAir Technologies Inc., a Canadian company located in Burnaby BC has the proprietary, fast cycle, compact PSA units that are being designed for a range of mobile applications; principally fuel cell oxygen enrichment and on-board generated hydrogen gas cleanup. QuestAir's adsorbent packs could be constructed incorporating zeolites designed purposely for containing battlefield contaminants. These packs, when mounted in an appropriate system, would offer protection for personnel as well as for the fuel cells. The complete packages would be significantly smaller size, and require lower energy because of lower pressure drop and higher separation efficiency than present state-of-the-art systems.

There is a reasonable prospect for a combined service device protecting both personnel and fuel cells. A compact oxygen enricher/purifier for a small fuel cell power pack could also provide personal survival decontaminated breathing air for personnel using the power pack. The crew of fuel cell operated weapon platform and those in proximity of the device could also be protected.

Fundamental research on new catalytic material is also required. New fabric-like filter media that can be integrated into soldier's environmental clothing, sleeping bags, tentages, causality bags and deployable shelters will be required. New filter media that are compact, low loss, washable, floodable, recyclable and able to withstand battlespace conditions are also required. It is also desirable to develop deployable "rejuvenator" that can recycle and recharge filter media in the mounted or dismounted locations. It is highly desirable that the rejuvenator technology will be integrated into the filter media, such that the filter media can be reactivated/rejuvenated by application of electricity and purging air.

4 PIEZOELECTRIC POWER GENERATION

Piezoelectric materials generate electrical charge when they are mechanically deformed. Alternatively, if a voltage is applied across a piezoelectric material, mechanical deformation or deflection results. This phenomenon forms the basis for a broad range of piezoelectric sensors and actuators. The same phenomenon can also be used for the generation of electrical power, which is the subject of this section.

4.1 State-of-the-Art

4.1.1 Piezoelectric Basics [1]

Two of the most commonly used industrial piezoelectric materials are lead zirconate titanate (PZT) and polyvinylidene fluoride (PVDF). PZT is a brittle ceramic material and, while it is commonly used in sensor applications, it is not suitable for piezoelectric power generation as it will break when deformed significantly. Much more promising for power generation application is PVDF and its copolymers, which are piezoelectric polymers. These polymers are very flexible and can undergo large deformations before breaking.

In a practical PVDF sensor or power generation device, the two surfaces of the polymer film are coated with a conductive material to act as electrodes as shown in Figure 7. Deformation of the film either by stretching it along the length of the material (1-axis) or compressing the material along the 3-axis, results in the generation of charge at the surface and a voltage appears between the two electrodes. The amplitude and frequency of the induced voltage is directly proportional to the mechanical deformation of the piezoelectric material. The electric charge developed by stressing the piezoelectric film will decay with time because of the internal resistance of the film. For this reason, true DC generation is not possible. The electrical charges developed across a piezoelectric film decay with a time constant that is dependent on the dielectric constant and the internal resistance of the piezoelectric film material.

The piezoelectric properties of a material are characterized by piezoelectric constants, d_{3n}, and g_{3n}. These coefficients relate the stress to the induced charge density and voltage respectively.

Under short circuit conditions, the generated charge density is given by

$$\frac{Q}{A} = d_{3n} X_n \qquad (1)$$

where Q is the charge developed, A the electrode area, X_n is the applied stress (N/m^2) and n is the axis of applied stress. The piezoelectric coefficient, d_{3n}, has units of $(pC/m^2)/(N/m^2)$.

Under open circuit conditions, the induced voltage is given by

$$V_0 = g_{3n} X_n t \qquad (2)$$

In this expression, V_0 is the induced voltage and t is the thickness of the piezoelectric film. The piezoelectric coefficient, g_{3n}, has units of $(V/m^2)/(N/m^2)$.

Typical parameters for PVDF are given in Table 13. From these parameters it is seen that energy conversion is most efficient when the piezoelectric film is compressed along the 3-axis. The amount of power that can be produced by compressing the film in the 3-direction is, however, relatively small because of the high Young's Modulus ($Y=2$ - 4×10^9 N/m^2) of the material. It thus takes very high forces to generate significant amounts of power when the piezoelectric film is used in the 33 mode. In spite of this, this mode can be useful in certain applications such as the explosive generation of power.

On the other hand, the bending of the piezoelectric film to take advantage of the materials 31 mode is much easier. To stress the material in the 31 mode, the material can either be laminated to a rigid backing to form a cantilever structure or laminated onto a clamped compliant plate. In either case, the force applied to the surface of the membrane is transferred into a stretching force that stretches the membrane. For an equivalent load on the surface of the membrane, the voltage generated in the stretching mode is typically 2 orders of magnitude higher than that obtained by the same load when it is applied in the compressive mode. This is because, in the stretching mode, the force ends up being applied to the cross-sectional area of the film rather that to the total film surface area. In the following discussion, power generation using both modes will be discussed.

Table 13: Properties of PVDF Film (from [1])

Symbol	Parameter		PVDF	Copolymer	Units
t	Thickness		9, 28, 52, 110	Various	μm (micron, 10^{-6})
d_{31}	Piezo Strain Constant		23	11	10^{-12} $\frac{m/m}{V/m}$ *or* $\frac{C/m^2}{N/m^2}$
d_{33}			-33	-38	
g_{31}	Piezo Stress constant		216	162	10^{-3} $\frac{V/m}{N/m^2}$ or $\frac{m/m}{C/m^2}$
g_{33}			-330	-542	
k_{31}	Electromechanical Coupling Factor		12%	20%	
k_t			14%	25-29%	
C	Capacitance		380 for 28μm	68 for 100μm	pF/cm² @ 1kHz
Y	Young's Modulus		2-4	3-5	10^9 N/m²
V_0	Speed of Sound	stretch:	1.5	2.3	10^3 m/s
		thickness:	2.2	2.4	
p	Pyroelectric Coefficient		30	40	10^{-6} C/m² °K
ε	Permittivity		106-113	65-75	10^{-12} F/m
$\varepsilon/\varepsilon_0$	Relative Permittivity		12-13	7-8	
ρ_m	Mass Density		1.78	1.82	10^3kg/m
ρ_e	Volume Resistivity		$>10^{13}$	$>10^{14}$	Ohm meters
$R_\square$	Surface Metallization Resistivity		2.0	2.0	Ohms/square for CuNi
$R_\square$			0.1	0.1	Ohms/square for Ag Ink
$\tan \delta_e$	Loss Tangent		0.02	0.015	@ 1kHz
	Yield Strength		45-55	20-30	10^6 N/m² (stretch axis)
	Temperature Range		-40 to 80	-40 to 115...145	°C
	Water Absorption		<0.02	<0.02	% H_2O
	Maximum Operating Voltage		750 (30)	750 (30)	V/mil(V/μm), DC, @ 25°C
	Breakdown Voltage		2000 (80)	2000 (80)	V/mil(V/μm), DC, @ 25°C

4.1.2 Theoretical Power Output for a Piezoelectric Film Used in the Stretching Mode

The theoretical electrical output and the mechanical-to-electrical conversion efficiency of a piezoelectric generator operating in the stretching mode has been studied in detail by Schmidt [2]. Some of the main results of this analysis are presented here.

In Schmidt's analysis, he calculated the theoretical energy output per unit volume of PVDF using the d_{31} piezoelectric coefficient and assuming that the film was utilized in a bimorph bending mode of operation. In making this calculation, two limiting factors were considered. The first was the yield strain of PVDF beyond which the membrane breaks and the second factor is the electrical breakdown voltage of the membrane that limits the voltage that can be induced. The configuration being considered is shown schematically in Figure 7. The equivalent circuit for the piezoelectric material consists of a voltage source in series with a capacitor, C, and a resistance, R_e, as shown in the left hand side of Figure 7.

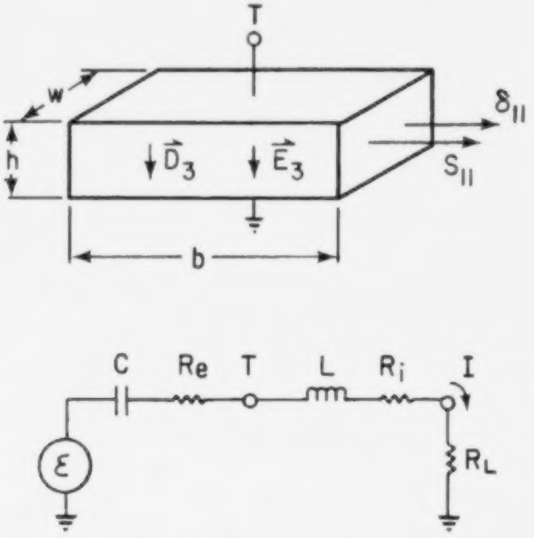


Figure 7: Schematic of a Piezoelectric Generator Operating in the Stretching Mode and its Equivalent Circuit Coupled to a Resonant Inductor and Load (from [2])

To optimize the output power by minimizing the source impedance, the capacitive part of the source impedance was cancelled by adding a suitable inductor as shown in Figure 8. At resonance, the output power is limited by the resistive components of the PVDF impedance and the inductor impedance. Using this approach, Schmidt showed [2] that, at a frequency of 1 kHz, the power output is as high as 100 W/cm^3 and that the efficiency can be as high as 70%. These results are shown in Figure 8.

For the non-resonant case, where inductance is not added to cancel the generator capacitance, the power density drops to about 19 W/cm^3 and the efficiency to about 6%.

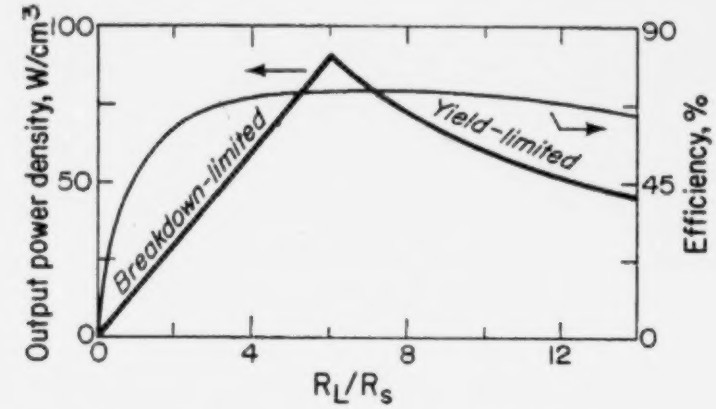


Figure 8: Maximum Power Density and Efficiency for a PVDF Generator Oscillated at 1 kHz

4.1.3 Theoretical Power Output for a Piezoelectric Film Used in the Compression Mode

The use of piezoelectric film in the compressive mode is potentially useful as a pulse power source. The high stress necessary to generate significant energy in this mode can come from an explosive source to generate a very high-pressure impulse. This situation is illustrated in Figure 9.

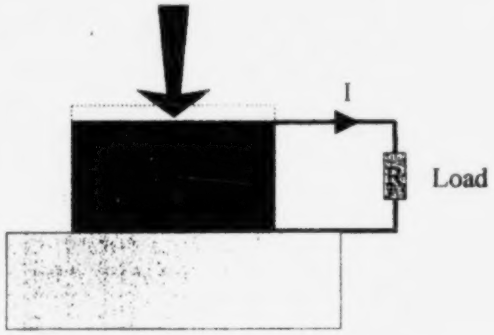


Figure 9: Pulse Power Generation: Piezoelectric Film in the Compression Mode

From equation (2), the electric field in the material is given by

$$E = g_{33} \cdot P \tag{3}$$

where P is the applied pressure.

The energy density of the electric field in the compressed piezoelectric material is then given by

$$W = \frac{E \cdot D}{2} (J/m^3) \tag{4}$$

where $D = \varepsilon_0 \cdot \varepsilon_r \cdot E$ and therefore we can rewrite (4) as

$$W = \frac{\varepsilon_0 \cdot \varepsilon_r \cdot (g_{33})^2}{2} \cdot 10^{-6} \cdot P^2 (J/cm^3) \qquad (5)$$

A graph showing energy density as a function of pressure is shown in Figure 10. The data shows that, for a pressure of 10 GPa, the energy density is about 600 J/cm^3. This can be compared with an energy density of about 360 J/cm^3 for a nickel/cadmium battery or about 1440 J/cm^3 for a lithium/sulphur dioxide battery. In addition, if we assume that the pressure impulse lasts 1 µs, the power density for the device is 0.6 GW/cm^3. It is thus seen that an explosively driven piezoelectric device has the potential to be a very compact pulse power source [3].

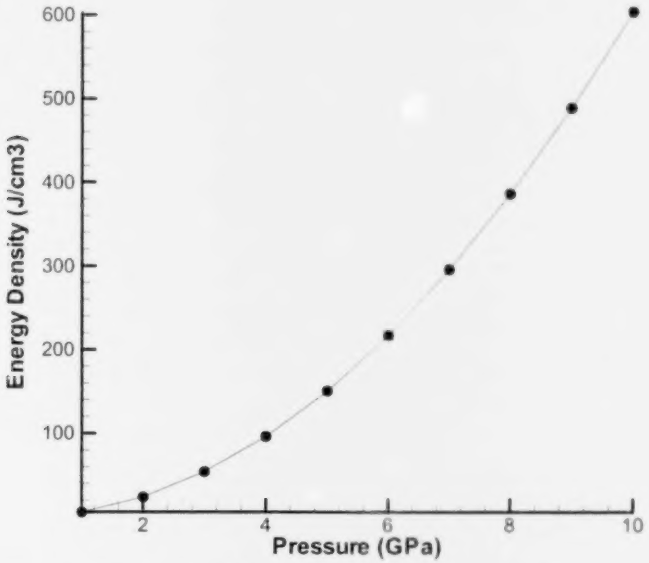


Figure 10: Energy Density of a Piezoelectric Generator in the Compressive Mode

4.2 Technology Trends

4.2.1 Energy Harvesting

As the size and power requirements for microelectronic devices decreases, there is considerable interest in the possibility of being able to "harvest" sufficient energy from the environment to power the electronic device. Piezoelectric power generation from kinetic energy sources in the environment is potentially attractive and is being considered. Some applications that are being considered include the following.

4.2.1.1 Human Powered Wearable Computers and Sensors

There is an increasing interest in developing [4] "wearable computers" that can be incorporated into clothing (e.g. shoes or jacket) or into wearable accessories such as sunglasses. This level of access to computers has the potential to revolutionize how computers are used. Developments in this area are clearly potentially significant to the military. Sufficient power might be able to be obtained in this way to power sensors and/or low power communications systems. While computer and electronic systems have been reduced in size to accommodate this vision, power systems are still bulky and inconvenient. If energy can be harvested by using power generated by the user's actions, problems associated with the provision of power will be alleviated.

Starner [4] has carried out a study of the potential physiological sources of power available for harvesting. Sources that he has examined include:

- body heat;
- breath;
- blood pressure;
- upper limb motion ;
- finger motion, and;
- walking

Of these potential sources, harvesting power during walking appears to offer the best promise. Starner [4] has estimated that up to 67 watts of power is available when the heel strikes the ground during a brisk walk (68 kg person taking two steps per second and raising the heel 5 cm). In an attempt to harvest some of this energy, Kymissis et al [5] have incorporated piezoelectric devices into the soles of a pair of shoes. In their experiments, both a PZT unimorph and a PVDF stave were incorporated into a pair of running shoes as shown in Figure 11. The energy produced was relatively small, approximately 1 mJ/step for the PVDF stave and 2 mJ/step for the PZT unimorph. The average power produced by the two devices was 1.1 mW and 1.8 mW respectively. The authors demonstrated that the piezoelectric shoe inserts generated sufficient power to operate an RF tag system that transmitted an ID code while walking.

To date, the power electronics that has been integrated with the piezoelectric devices has been relatively simple. In their paper, Kysmissis et al [5] state that there is considerable potential to increase overall system efficiencies. Incorporation of an inductive component as part of the load to cancel the capacitive portion of the source impedance as discussed in Section 1.2 is one option they discuss.

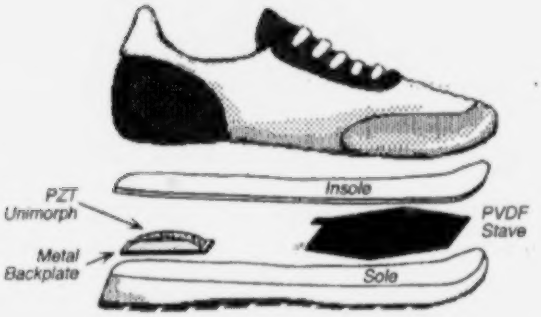


Figure 11: Piezoelectric Inserts into a Pair of Shoes (from [5])

4.2.1.2 Harvesting Energy from the Oceans and Rivers

The harvesting of energy from the mechanical energy of waves and flowing water has also been proposed through the use of "piezoelectric eels" in a DARPA sponsored program [6] being carried out by Ocean Power Technologies Inc. The goal of this program is to generate electrical energy from flowing water for long endurance military missions, unattended sensors or small robotic devices.

In this device, the flow of water causes motion in the piezoelectric eel that generates electricity. Power electronics are needed to rectify the AC power to generate DC power that can be stored for later use. The goal of the project is to produce a device that is capable of generating 30 watts from a device having an area of 900 cm^2 in a stream with a flow velocity of 1.5 m/s.

4.2.1.3 Harvesting Wind Energy

Several designs of piezoelectric wind generators have been investigated by Schmidt [7]. Potential advantages of a piezoelectric wind generator over a conventional wind generator include improved safety by the elimination of a high-speed rotor to both people and wildlife (birds) and improved reliability because of the elimination of moving parts. In terms of simplicity, of particular interest is the oscillating blade generator developed [7] and patented [8] by Schmidt. This design is based on a cantilever-mounted spring with a plastic blade mounted at the end. PVDF sheets are mounted on each side of the plastic blades. Oscillation of the structure in the wind generates electricity. Such a design could be attractive for remote power generation.

4.3 Research and Development Opportunities

A watching brief should be maintained to keep abreast of the potential use of piezoelectric devices for energy harvesting applications.

As part of a program in pulse power technology, preliminary studies should be undertaken to investigate the potential of explosively driven piezoelectric generators to provide power for HPM and NNEMP devices.

5 THERMOELECTRIC POWER GENERATION

When heat flows in a conductive material, the charge carriers in the material are also carried along resulting in a potential difference between the ends of the material. This effect, called the Seebeck effect, is the basis of the thermoelectric generation of electricity.

5.1 State-of-the-Art

5.1.1 Thermoelectric Basics [1]

The ability of a material to generate a potential when exposed to a thermal gradient is determined the Seebeck coefficient, α, which is usually measured in μVK^{-1}. The overall "goodness" of a thermoelectric material can be characterized by the figure-of-merit,

$$Z = \frac{\alpha^2 \sigma}{\lambda}. \tag{1}$$

From this expression, it is seen that good thermoelectric materials should have a large Seebeck coefficient, α, a poor thermal conductivity, λ, to retain the heat at the junction and good electrical conductivity, σ, to minimize Joule heating caused by the flow of current. Most metals have small Seebeck coefficients, generally less that 10 μVK^{-1}, which corresponds to generating efficiencies of less that 1%. The development of practical thermoelectric generators became possible with the development of semiconductors with Seebeck coefficients in excess of 100 μVK^{-1} in the 1950's. At the same time there was strong military interest in thermoelectric generators that spurred the development of suitable materials.

Based on this phenomenon, a thermoelectric generator can be constructed by connecting the hot ends of two dissimilar conductors to form a hot junction and by connecting a load to the cold end of the two materials as shown in Figure 12.

Figure 12 shows a load resistance, R_L, connected across the terminals at the cold junction. Suppose the heat source supplies heat at a rate q, so as to maintain the temperature difference $\Delta T = T_h - T_c$. The voltage produced by the generator is then

$$\Delta V = (\alpha_p - \alpha_n)(T_h - T_c) \tag{2}$$

The power delivered to the load is then

$$W = \left[\frac{(\alpha_p - \alpha_n)(T_h - T_c)}{(R_L + R)} \right]^2 R_L \tag{3}$$

where R is the resistance of the thermoelectric elements.

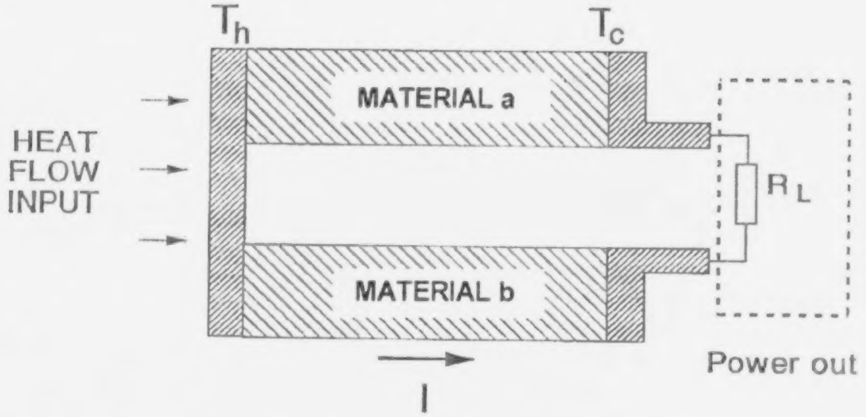


Figure 12: A Thermocouple as a Power Generator

The efficiency, η, of the generator is equal to the ratio of the useful work, W, delivered to the load to the heat, q, supplied to the hot junction. It has been shown [2] that the maximum efficiency of the generator can be written

$$\phi_{\max} = \gamma\eta \tag{4}$$

where

$$\gamma = \frac{T_h - T_c}{T_h} \tag{5}$$

and

$$\eta = \frac{(1 + ZT)^{1/2} - 1}{(1 + ZT)^{1/2} + T_h / T_c} \quad where \quad T = \frac{T_h + T_c}{2} \tag{6}$$

The efficiency of the thermoelectric generator is thus seen to be the product of the Carnot efficiency, γ, and η, which is dependent on the properties of the thermocouple materials.

The overall efficiency is seen to depend on the temperature difference between the hot and cold junctions, the average temperature of operation and the figure of merit, Z, of the thermocouple. Consequently, materials that possess large Z values over the intended temperature range of operation are desirable. The theoretical efficiency of a thermoelement fabricated with a semiconductor having $Z=3 \times 10^{-3}\ K^{-1}$ and operating over a temperature difference of 100°C and a cold junction temperature of 300°K is about 5.5%. In practice, heat losses would reduce this efficiency by about 50% resulting in a practical efficiency of less than 3%. Thermoelectric generators seldom achieve more than 25% of the theoretical Carnot efficiency.

5.1.2 Thermoelectric Materials [3]

Established thermoelectric materials fall into three categories depending upon their temperature range of operation.

5.1.2.1 Low Temperature Materials (<450 K)

Bismuth telluride and its alloys have the highest figures-of-merit (up to 3×10^{-3} K^{-1}) and are extensively employed in low temperature generators and refrigeration. The maximum operating temperature of bismuth telluride alloys is about 450 K.

5.1.2.2 Medium Temperature Materials (< 1000 K)

Alloys based on lead telluride have the next highest figures-of-merit with silicon germanium alloys having the lowest. Lead telluride alloys have an upper operating temperature of about 1000 K and are used in generator applications.

5.1.2.3 High Temperature Materials (< 1300K)

Silicon germanium has the lowest figure-of-merit but is able to operate for long periods of time at high temperature (up to 1300 K). This material is also used in generator applications especially for space applications.

Although the figure-of-merit for the three classes of materials differs substantially so does the operating temperature so, in practice, the performance of all of the materials is comparable.

5.1.3 Thermoelectric Generator Design

A modern thermoelectric generator is normally built from of a number of n- and p-type semiconductor thermoelements that are connected electrically in series with metal connecting strips. These thermoelements are sandwiched between two electrically insulating but thermally conducting ceramic plates to form a module as illustrated in Figure 13. Provided a temperature difference is maintained across the module, electrical power will be delivered to an external load and the device operates as a generator.

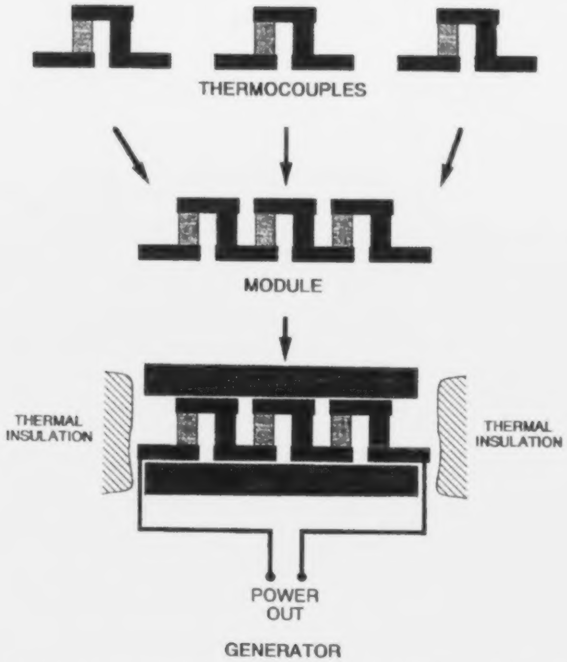


Figure 13: Design of a Thermoelectric Generator (from [3])

Since the early 1960s, a large number of applications have arisen that require an autonomous source of electrical power. These applications include the exploration of space, cardiac pacemakers, provision of power at remote and hostile sites for communications, power for oil and mineral exploration, and silent, field power for the military. Thermoelectric generators are ideally suited to such applications. In these applications, the inherent reliability, absence of moving parts, and silent operation of the thermoelectric generator generally outweigh their relatively high cost and low efficiency (typically less than 3%). Advantage can be taken of the simplicity and ruggedness of thermoelectric generators as compared with other electromechanical generators, in particular engine generators. In situations where periodic refueling is possible and oxygen available, fossil fuels can be employed as the heat source. Hydrocarbon fuels have an energy density about 50 times that of a lithium battery and so, provided that the conversion efficiency is better than 2%, a hydrocarbon-fueled system can provide a lighter and less bulky source of long-term electrical energy than batteries. When annual refueling is not possible, or if oxygen is not available, radioactive isotopes can serve as the heat source, enabling the generators, which are referred to as radioisotope thermoelectric generators or RTGs, to operate unattended for extended periods. As an example, the Voyager spacecrafts launched in 1977 to explore the outer planets have been powered by RTGs for longer than 22 years.

5.1.4 Generator Types and Applications

5.1.4.1 Hydrocarbon Fueled Thermoelectrics [4]

At the present time, there are two companies that produce hydrocarbon fueled thermoelectric generators for the commercial market. These companies are Global Thermoelectric Inc. in Alberta and Teledyne Energy Systems in the U.S. The Global Thermoelectric Inc. technology originated at the 3M company in the U.S. A group of the 3M employees acquired this technology and then moved their operations to Alberta. Teledyne Energy Systems had its origins in General Instruments in the U.S.

Most of the thermoelectric generators produced by these two companies are fueled by gaseous fuels such as propane or natural gas (methane). Commercial generators are produced covering a power range from 10 to 550 watts. The main characteristics of these generators are given in Table 14.

Table 14: Characteristics of Commercial Thermoelectric Generators (from [4])

Manufacturer	Basic Model	Nominal Wattage	Natural Voltage	Watts at 12 V DC	Watts at 24 V DC	Fuel (LPG) kg/d	Price[a] (USD)
Teledyne	2T1	10	4.8	8	8	0.73	2295
Teledyne	2T2	20	9.6	17	17	1.46	2995
Global	5030	30	2.5	24	24	1.50	2715[b]
Teledyne	2T3	30	14.4	30	25	2.19	3420
Teledyne	2T4	40	19.2	36	36	2.91	4295
Global	TCELL 50	50	3.5	40	40	2.90	2284
Teledyne	2T5	50	24	50	50	3.63	5075
Global	5060	60	6.7	54	54	2.90	5220
Teledyne	2T6	60	28.8	60	60	4.36	5975
Teledyne	2T7	70	33.6	68	68	5.09	6895
Teledyne	2T8	80	38.4	79	74	5.81	7800
Teledyne	2T9	90	43.2	90	89	6.54	8500
Global	5120	120	6.7	108	108	5.8	5481
Global	5220	220	15	220	176	14.2	8039
Global	8550	550	27	480	550	38.0	16443

[a] Prices are based upon manufacturer's published list prices. Prices are in U.S. dollars

[b] Price includes a DC-DC converter.

In addition to gaseous-fueled thermoelectrics, there has been some work aimed at the development of liquid (primarily Diesel) fueled generators. This has been largely driven by the military for use as a method of delivering silent field power. Both DND and the US DoD have supported this effort.

The main features that have made the use of thermoelectric generators attractive for military applications include:

- no moving parts which lead to high reliability and low maintenance.
- long service life.
- adaptable to hostile environments.
- continuous and predictable power output.

Applications where thermoelectric generators have been used extensively include the following.

a) Communications Applications

Many of the mountaintop microwave repeater stations throughout out the world use thermoelectric power. These installations are generally remote. The generators are usually propane fueled and many are only visited for annual refueling and maintenance.

b) Pipeline Applications

Thermoelectrics are also extensively used on oil and gas pipelines monitoring, for provision of emergency power and for corrosion protection. For gas pipeline applications it is possible to tap into the line to obtain the fuel supply. This eliminated logistical problems that are often associated with provision of fuel.

5.1.4.2 Radioisotopic Thermoelectric Generators (RTGs) [5]

Radioisotopes can provide a very long-lived heat source that can be used to power a thermoelectric generator. In such a heat source, the heat is produced by the natural radioactive decay of the isotope. The main isotopes that have been used for this application include:

Co^{60},	5.25 y half-life,	0.31 MeV beta, 1.37 MeV gamma
Sr^{90},	25 y half-life,	0.54 MeV beta
Pu^{238},	92 y half-life,	5.14 MeV alpha, 0.04 MeV gamma

a) Terrestrial Applications

RTGs have been used to provide power at a number of remote terrestrial sites. Some of these applications include:

Weather Stations

The first terrestrial use of a RTG was to power an unattended weather station on Axel Heiberg Island in the Canadian Arctic. AN RTG based on the SNAP-3 RTG developed for space applications was used. This system provided 5 watts of continuous power to collect a variety of meteorological information. Similar systems were later installed in the Antarctic.

Navigation Aids

RTGs have also been used to power navigational aids. In 1965, AERE in Britain designed and built several RIPPLE generators that employed Sr^{90} and that were used to power navigation lights. In 1972, AECL developed an RTG based on the use of Co^{60}. Several of these systems were installed along the St. Lawrence Seaway.

b) Military Applications

The US military have employed RTGs to power a number of communication and detection systems. These have usually been in hostile environments.

The use of RTGs for terrestrial applications has decreased following an initial surge of interest. The decreased use of RTGs is partly related to a generally anti-nuclear sentiment with the public but also to the high cost and the fact that RTGs are generally longer lived than they need be to meet most of the requirements.

c) Space Applications of RTGs [6]

RTGs have been extensively used to provide power for long-lived space missions. A summary of the US use of RTGs in space is given in Table 15. This data shows that thermoelectric systems have provided reliable power for a wide range of space missions. Note that the early missions used lead telluride elements whereas later missions have used the higher temperature Silicon Germanium elements. The efficiency of the systems has been raised from about 5% in the early systems to about 6.6% with the most recent. Recently NASA has moved to a modular RTG design based on the use of a general-purpose heat source (GPHS). Each GPHS is designed to produce about 250 W of thermal energy or about 19 watts electrical at 30.8 V when coupled to the SiGe thermoelectric elements. The range of power can be varied from 19 W(e) if a single module is used up to 340 W(e) for a converter with 18 GPHS modules.

d) Medical Use of Isotopic Power Sources [3]

Miniature RTGs have been extensively used to power cardiac pacemakers. These pacemakers control heart rhythms by injecting electrical shocks into the heart muscles. Current RTG pacemaker "batteries" deliver from about 33 μW up to about 600 μW in the larger batteries. The material used for the thermoelectric elements for these RTGs is generally BiTe presumably to keep the operating temperature as low as possible. Pu^{238} has been the isotope of choice. The advantage of these miniature RTGs is that they have very long life after implantation thus minimizing the need for future surgical replacement of the battery.

Table 15: Summary of the Use of RTGs in US Space Missions [6]

Spacecraft	Source	T/E Materials	Launched	Life
Transit 4A	SNAP-3B7	PbTe	1961	> 15 y
Transit 4B	SNAP-3B8	PbTe	1961	9 y
Transit 5BN1	SNAP-9A	PbTe	1963	9 mo
Transit 5BN2	SNAP-9A	PbTe	1963	> 6 y
Apollo 12	SNAP-27	PbTe	1969	> 8 y
Apollo 14	SNAP-27	PbTe	1971	> 6.5 y
Apollo 15	SNAP-27	PbTe	1971	> 6 y
Apollo 16	SNAP-27	PbTe	1972	5.5 y
Apollo 17	SNAP-27	PbTe	1972	5 y
TRIAD	Transit-RTG	PbTe	1972	28 y
Nimbus III	SNAP-19B	PbTe	1969	> 2.5 y
Pioneer 10	SNAP-19	PbTe	1972	28 y
Pioneer 11	SNAP-19	PbTe	1973	27 y
Viking 1	SNAP-19	PbTe	1975	> 6 y
Viking 2	SNAP-19	PbTe	1975	> 4 y
LES-8	MHW-RTG	SiGe	1976	24 y
LES-9	MHW-RTG	SiGe	1976	24 y
Voyager 1	MHW-RTG	SiGe	1977	23 y
Voyager 2	MHW-RTG	SiGe	1977	23 y
Galileo	GPHS-RTG	SiGe	1989	11 y
Ulysses	GPHS-RTG	SiGe	1990	10 y

5.2 Technology Trends

5.2.1 Improved Thermoelectric Materials

Thermoelectric devices have a number of attractive features such as long life, the lack of moving parts, low maintenance and high reliability. In spite of these advantages, their use in both civilian and military applications has been very limited primarily due to the low efficiency of these devices. The use of thermoelectrics would be substantially increased if the efficiency of these devices could be increased.

The main difficulty is that available thermoelectric materials have limited performance. Thermoelectric materials are often characterized in terms of the dimensionless figure-of-merit

$$ZT = \frac{\sigma\alpha^2}{\lambda}T \tag{7}$$

The efficiency of the thermoelectric generator is directly dependent on the figure-of-merit as is shown in equations (4,6). Recently new programs have been initiated to develop new materials with substantially improved figure-of-merits.

Each of the most commonly used thermoelectric materials, such as Bi_2Te_3, PbTe, and SiGe, have a maximum ZT=~1. For these presently used thermoelectric materials, the maximum efficiency that can be expected is about 5%. If, on the other hand, the figure-of-merit, ZT, could be raised to 4 then the theoretical efficiency could be increased to possibly as high as 10%, approaching for example, the efficiency of small engine generators.

Theoretical work has shown [7] that there is no fundamental upper limit on ZT. The possibility for substantial improvement in thermoelectric efficiencies therefore exists. In response to this opportunity, in 1995 DARPA [8] initiated a program to develop new thermoelectric materials with substantially improved properties. The goal of this program is to "quadruple the figure-of-merit of thermoelectric materials, thus making the resulting devices competitive with conventional phase change systems".

Toward this end, a number of new materials have been identified that have the potential of substantially improved figure-of-merit. These materials [9] include: skutterudites, mesoporous materials, thin film/quantum well/quantum wire/quantum dot structures, intercalation compounds, doped polymeric materials etc.

Development of new materials is being assisted through the development of new synthetic techniques such as the use of combinatorial methods to rapidly synthesize large numbers of compounds and new screening methods that allow rapid screening of large numbers of compounds.

As a result of these new initiatives substantial progress has been made in recent years. In recent years, materials having ZT as high as 2 have been developed and there are indications that some materials may have a figure-of-merit as high as 3. It remains however to demonstrate that these materials can be turned into useful, high efficiency thermoelectric devices.

5.2.2 Miniaturization of Thermoelectric Devices [3]

The current trend toward miniaturization of electronic components and the development of "systems-on-a-chip" where sense, compute, actuate, control, communicate and power functions are located together is increasing the need for the development of miniaturization of power sources. In spite of their relatively low conversion efficiency, miniaturized thermoelectric generators can be attractive because of their inherent simplicity and reliability coupled with the very high energy density of hydrocarbon fuels.

Recent efforts have resulted in the development of microelectronic thermoelectric generators such as that illustrated in Figure 14 [10]. Note in this device that the height of the thermoelectric elements is only 1 μm. Techniques for the manufacture of microthermoelectric devices have been developed that allow microelectronic machining techniques to be used for fabrication thus allowing easy integration of the power source with other electronic and sensor components.

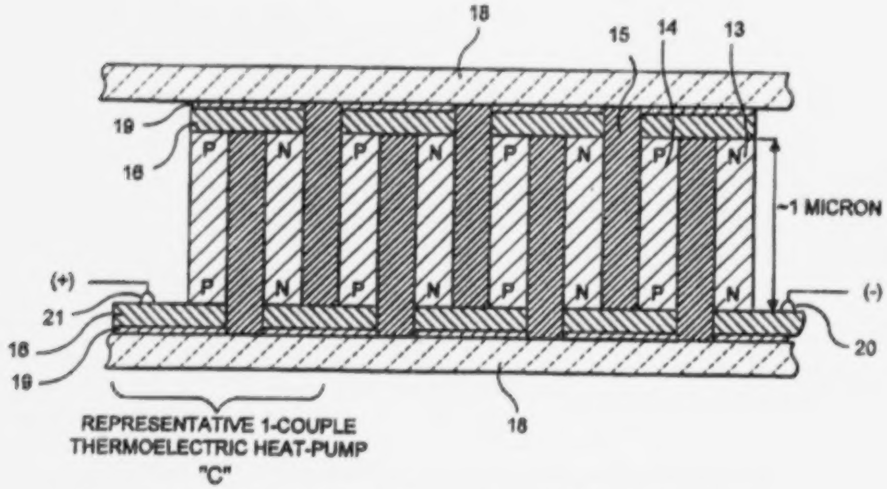


Figure 14: A Microelectronic Thermoelectric Device (from [10])

The development of a "highly-miniaturized, integrated, monolithically and batch-fabricated power generator with no moving parts, capable of powering MEMS devices" is being carried out at the University of Southern California under DARPA sponsorship. A further goal of this project is to "develop sufficient power to replace batteries in macroscale systems such as weapons, computers, radios and GPS receivers". Development of miniaturized thermoelectric generators is being carried out by a number of other workers [11,12] as well.

5.3 Research and Development Opportunities

The following are potential research opportunities that have been identified in the thermoelectric area:

a) Participation in the development of improved thermoelectric materials and the development of theoretical models to help identify potentially useful structures and materials is a research opportunity that should be considered in view of Canada's leading position in the thermoelectric industry. Recognition needs to be taken however of the substantial US military sponsored activity that is being supported and the limited capability that exists in Canadian university and government labs.

b) Development of "palm sized" TEGs capable of providing substantially higher energy density than existing batteries. Work needs to be done on compact combustor development, the production of small, low cost thermoelectric elements and system integration.

c) Development of micro TEGs for powering MEMS sensors and actuators.

6 THERMOPHOTOVOLTAIC POWER GENERATION

Thermophotovoltaic (TPV) devices are semiconductor diodes that directly convert photons from a black body radiating source at temperatures typically below ~2000°C into electricity. In this they are similar to solar photovoltaic (SPV) devices.

6.1 State-of-the-Art

6.1.1 Thermophotovoltaic Basics [1]

There are, however, several significant differences between TPV and SPV devices. These differences include:

a) TPV devices operate at power densities of the order of 100-1000 times greater than SPV devices;

b) TPV diodes exhibit intrinsically higher current than SPV diodes;

c) The power spectrum of the sun is comparable to a black body source with T_s = 6000 K compared to a TPV where $T_s <$ 2000°C;

d) in a TPV device, the emissivity of the source can be tailored to match the optical band gap of the semiconducting diode with significant improvements in the efficiency of converting the power radiated by the radiating source into electric power produced by the TPV device.

The components of a TPV power system are inherently simple as shown in Figure 15. The core of the system is the heat source. The purpose of the heat source is to convert the chemical energy in the fuel into heat and transfer that heat to the emitter. The emitter is a high temperature ceramic material that is heated up to 2000°C. Because of its temperature, the emitter emits electromagnetic radiation in the infrared region. This radiation is focused onto the PV cells. Most TPV systems include a filter, because the PV cells only convert a narrow band of the infrared spectrum into power. The filter reflects the unusable part of the spectrum back into the heater to increase efficiency. The PV cells convert the portion of the radiation that passes through the filter into DC power. The portion of the energy that is not converted to power must be removed as waste heat. A recuperator is added to boost the efficiency of the system by transferring the waste heat in the combustion exhaust stream to the combustion air input. Finally, an air/ fuel delivery system is required: this may include air fans, a fuel pump, and controls.

TPV generators have a number of potentially attractive characteristics that make them suitable for meeting military power requirements. These include:

- No moving parts in the main power stream
- Inherently quiet
- Capable of using logistic fuels
- Multifuel capable
- Moderate efficiency
- Tolerant of low temperature

Negative characteristics of TPV generators include:

- Operate at elevated temperature
- Thermal signature
- Low state of development, little system experience.
- Not completely quiet (acoustic signature)

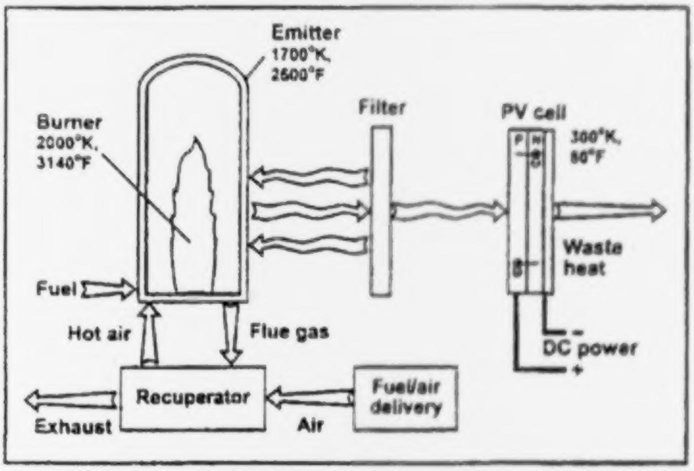


Figure 15: TPV System Components

6.1.2 TPV Development and Applications

To meet the requirement for improved compact, lightweight and portable sources of power in the 50 W to 3 kW range for Army field applications, the U.S. Army Research Office and DARPA have initiated a substantial research and development program in the TPV area. More than $16M USD has been spent [2] on basic research in the TPV area to date. The report of a DoD sponsored workshop on TPVs [3] held in 1996 provides an update on R&D to that point.

6.1.2.1 Component Optimization

The overall efficiency of a TPV system can be defined as the product of three efficiency terms as shown in equation (1)

$$\eta = \eta_{\text{diode}} \cdot \eta_{\text{filter}} \cdot \eta_{\text{design}} \tag{1}$$

where η_{diode} is the diode efficiency, η_{filter} is the efficiency of the filter and η_{design} takes into account engineering losses in the design of the system. To a large extent, these factors can be optimized individually since they are largely uncoupled. An overview of the development status of TPV components and systems has been given by Black, Baldasaro and Charache [1].

At an operating temperature of 2000°C or less, blackbody emissions are largely in the infrared. To optimize diode efficiency low bandgap TPV diodes (bandgap in the range from 0.2 -0.5 eV for operating temperatures from 1200K - 2500K) are required. The best low bandgap diodes that have been produced to date are based on a quaternary In/Ga/As/Sb semiconductor. Diodes constructed from these materials have an achieved diode efficiency of 26% for a source temperature of 1200°C and a diode temperature of 25°C. Black et al suggest that, in order to improve diode efficiencies further, improvements in diode material and construction are needed. They estimate that further improvements in TPV diode performance is possible with diode efficiencies greater that 35% and power densities as high as 1 W/cm^2 possible at 1100°C.

As only photons with energy greater that the bandgap of the diode can produce charge carriers, reflecting the lower energy photons back into the thermal source can substantially increase the efficiency of a TPV generator. To achieve this reflection, interference and/or plasma filters are used. To date the best filter efficiency has been achieved using a tandem filter that combines both a plasma and an interference filter. Using this technology, filter efficiency as high as 65% has been achieved. Black et al [1] predict that this value may be raised as high as 91% with further development.

Based on the efficiencies given above, the maximum TPV efficiency is calculated to be approximately 17% at the moment, with projections that this may rise as high as 30% in the future. Not considered in this analysis however other losses associated with the TPV generator design. These additional losses are included in the η_{design} term and include such things as:

- convective and conductive heat transfer losses
- resistive losses
- parasitic photon absorption in inactive areas

These design losses are large and significantly reduce the over all TPG generator efficiency. Typically η_{design} is about 0.5. The largest contribution to system inefficiency has been shown to be parasitic photon absorption in inactive areas.

The highest overall efficiency that has been achieved in a TPV system is 7.2%.

6.1.2.2 TPV System Development

Under US Army sponsorship, a number of prototype TPV systems have been developed and evaluated. These include:

a) 20 W TPV Battery Substitute

Thermo Power Corp in collaboration with JX Crystals and Essential Research have developed [4] a prototype 20 W TPV system as a substitute for the BA-5590 battery. The 20 W TPV system was intended to be used in combination with a BB-390A/U rechargeable battery and to be fueled using replaceable propane cartridges. The overall efficiency of this prototype was only about 1%.

b) 500 W Diesel Fueled TPV System

McDermott Technology Inc. in collaboration with JX Crystals and BWX Technologies Inc are developing [5] a 500 W TPV system capable of using Diesel fuel. The system uses high efficiency GaAs photocells and thermal recuperation to improve the efficiency. The estimated efficiency of the system is 8-10% with this rising to 15-20% in the long term.

c) TPV Battery Charger

Quantum Group Inc. is developing [2] a TPV generator for battery recharge applications. The initial prototype produced 112 W and used propane as a fuel. Initial efficiency was 1-2%. Development work to improve ruggedness and system efficiency is continuing.

6.2 Technology Trends

The development of TPV technology is still in its infancy and considerably more work is required to demonstrate the usefulness of this technology as a power source for military applications. While more work is required to optimize diode and filter efficiencies, at the present time the main problems to be solved [3] are engineering in nature and relate to such aspects as:

a) System design to:
  - reduce weight
  - optimize power and energy density
  - system life
  - ruggedization

b) Matching of the emitter, filter and photovoltaic cell
  - materials compatibility
  - effects of thermal cycling

c) Burner and Recuperator Design
  - multifuel capability
  - cold start-up
  - orientation independence

6.3 Research and Development Opportunities

TPV generators have the potential to substantially improve energy density for the provision of power for the soldier in the field and to reduce acoustic signatures. These systems should help overcome the limitations of existing batteries, at the low power end, and engine generators at the high power end. It should be noted however that both fuel cells and TEGs will compete to meet these requirements.

There are also many similarities in the materials, fabrication and burner designs needed for TPV systems and those needed for thermoelectric systems. Global Thermoelectric is a world leader in the development and manufacture of thermoelectric systems. This expertise could be used as the base for the development and manufacture of TPV systems in Canada.

M. Whale is doing the only known Canadian TPV research and development work that we are aware of. He works at the Institute of Integrated Energy Systems at the University of Victoria and is specifically working in the area of microscale thermophotovoltaic devices.

7 MAGNETOHYDRODYNAMIC POWER GENERATION

In magnetohydrodynamic (MHD) power generation [1], the motion of a conducting gas is flowing through a magnetic field generates an electric field that is used to produce power as shown in Figure 16. In order to use this power, electrodes must be in contact with the gas to permit a flow of current. In this configuration, one of the electrodes (the cathode) emits electrons and the other electrode (the anode) collects them.

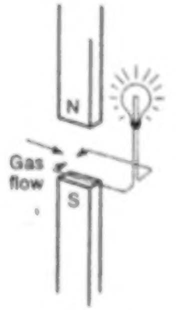


Figure 16: Illustration of MHD Power Generation

The conducting gas used in the power generation process is produced by partially ionizing the gas by heating it. MHD generators can be classified into two major types: **Open-cycle** generators where the ionized gas is produced in a combustion process, passed through the generator and discarded, and; **closed-cycle** generators in which the working fluid is heated and ionized inside a closed container, passed through the generator and then collected and reused. These two major types are discussed briefly below.

7.1 State-of-the-Art

7.1.1 Open Cycle MHD Generators

To produce the ionized gas for an open-cycle MHD power generator, a fossil fuel such as coal, oil or natural gas is burned at a temperature high enough to produce the required ionization. For normal combustion products, the temperature required to produce sufficient ionization is about 4500 K. This temperature is too high for practical use. To overcome this difficulty the gas is seeded with an element, such as potassium, that has a lower ionization potential. With 1% potassium in the flow, efficient MHD power production can be achieved at an upper operating temperature of 2800 K. This "seed" potassium must be collected and recycled in the process. Preheating of the combustion air or oxygen enrichment is needed to achieve this temperature. At a temperature of about 2200 K, the conductivity of the gas stream has dropped sufficiently low that MHD power production is no longer attractive. This very limited operating temperature range means that the Carnot efficiency for an open-cycle, single stage MHD power generator is only about 28%. To overcome this difficulty, the concept of a combined cycle MHD/steam power plant has been developed. In this combined system, the MHD generator is used as a topping cycle, the waste gas from the MHD process is then used in a steam Rankine cycle process to extract the lower temperature thermal energy. The overall efficiency of such a plant can be as high as 55%.

The materials problems associated with MHD power production are severe and, to date, MHD has not been used in Commercial power production systems. A number of demonstration systems have been built however. Open-cycle MHD plants are only suitable for large-scale power generation, that is for central power generation. For this reason open-cycle MHD power systems are of little military significance and are not discussed further in this document.

7.1.2 Closed-Cycle MHD Power Production

In a closed-cycle MHD system, the working fluid is heated from an external heat source and then passed through the MHD generator. Because the working fluid is recycled, the cost of the fluid is no longer of primary concern and a much wider range of options are available. Helium is the most attractive gas and cesium can be used as a seed material. While the operating temperatures are lower that those of an open-cycle system, a combined cycle is still generally used to raise overall system efficiency.

As an alternative to using a gas as the working fluid in a closed-cycle MHD power generator, closed-cycle liquid metal MHD systems are also being developed. The higher conductivity of a liquid metal system enables extraction of about 10 times the power for a given volume of fluid that is possible in a gas MHD system. This means that a more compact system is possible. The thermal efficiency of the liquid metal MHD systems is lower however.

Liquid metal MHD systems have been considered for provision of power for space applications and for submarine propulsion as well as for central power generation [2]. A nuclear source can be used to provide the heat for the space and submarine applications.

7.1.3 MHD Propulsion

MHD seawater propulsion can be achieved by passing an electrical current through the seawater in the presence of a strong magnetic field. The applied magnetic field interacts with the electrical current to eject the seawater from the MHD device to produce the necessary propulsion. In this process, the applied electrical energy is converted into kinetic energy in the seawater. This process is the reverse of MHD power generation.

MHD seawater propulsion has several potential advantages over the use of propeller systems. Some of these advantages include: reduced vibration in the ship or submarine; reduced acoustic signature; and higher speed than can be achieved with the use of propellers because of cavitation.

The use of MHD propulsion has been studied for many years but, to date, has not proved to be a practical. Difficulties result from the relatively low conductivity of seawater and the maximum magnetic fields that are achievable.

7.2 Technology Trends

There are no specific trends in the development of MHD technologies.

7.3 Research and Development Opportunities

Initiation of R&D in this area is not recommended. The costs are very high and the number of applications is very limited.

8 EXPLOSIVELY DRIVEN MAGNETOCUMULATIVE GENERATORS

In many military applications, there is a need for a source that is both lightweight and that is capable of delivering very high power, short duration pulses. Such applications include electromagnetic guns, high power microwave and non-nuclear EMP (NNEMP) devices and reactive armor. One device that has the capability to meet these requirements is the explosively driven magnetocumulative generator (EMG).

8.1 State-of-the-Art

8.1.1 EMG Basics

The physical principles behind the operation of the EMG have been well documented [1,2]. In this device, explosives are used to compress an initially induced magnetic field by driving together some or all of the conducting surfaces that contain the magnetic flux. The work done by the moving conductor against the magnetic field results in an increase in the stored magnetic energy. The additional energy is provided by the chemical energy of the explosive.

Figure 17 shows the basic components of a helical or spiral type EMG. The generator consists of an external helical winding and an inner metallic cylinder, or armature, that is loaded with explosive. An initial flux is supplied to the generator from a source such as a capacitor and, when the flux is at a maximum, the explosive is detonated. On detonation, the armature expands resulting in a metallic cone that travels at the detonation velocity. This expanding cone compresses the initial magnetic flux resulting in energy magnification. The energy generated by the EMG is fed into the external load coil that is shown at the bottom right of Figure 17.

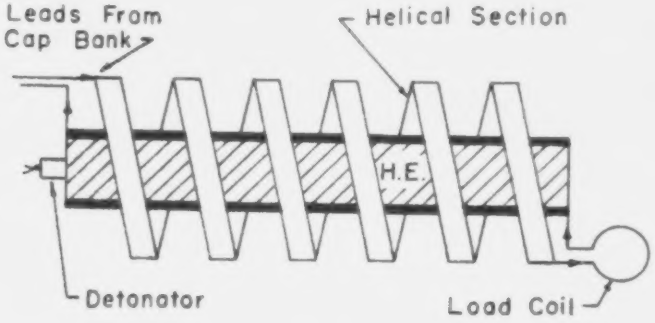


Figure 17: Schematic of a Helical EMG (from [2])

The equivalent electrical circuit of the generator is shown in Figure 18. In this figure, the generator inductance is $L_G(t)$, the external load inductance is L_0 , the stray inductance (in leads etc) is l_0, the load inductance is L_1 and the circuit resistance is R. Following explosive initiation, expansion of the armature progressively shorts out the windings as the conical front proceeds down the armature. The inductance of the generator is approximately proportional to the square of the number of turns and inversely proportional to the remaining length over which the turns are spaced. The generator inductance, L_G, therefore, varies more or less linearly with time from its initial value, L_0, to zero at the end of the expansion of the armature.

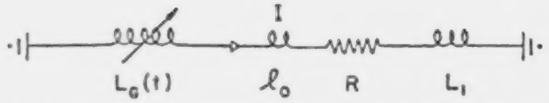


Figure 18: Schematic of the Explosively Driven, Magnetocumulative Generator

If the circuit is perfectly conducting, R=0, then the magnetic flux, LI, is conserved and we can write

$$(L_G + l_0 + L_1)I = (L_0 + l_0 + L_1)I_0 \tag{1}$$

At the end of compression, L_G=0 and the final current becomes

$$I_f = \frac{(L_0 + l_0 + L_1)}{(l_0 + L_1)} I_0 \tag{2}$$

Noting that the inductive energy of the circuit is given by

$$E = \frac{1}{2} LI^2 \tag{3}$$

The energy multiplication of the device is then given by

$$M = \frac{E_f}{E_0} = \frac{(L_0 + l_0 + L_1)}{(l_0 + L_1)} \tag{4}$$

Equation (4) shows that, to get high energy multiplication, the load inductance, L_1, and the stray inductance, l_0, must be kept much smaller than the initial inductance, L_0, of the generator.

The energy multiplication factor, M, given in equation (4) represents the maximum energy multiplication that can be achieved. In general, the energy multiplication will be lower than this as a result of resistive losses in the system. In can be shown [1] that, for energy multiplication to occur, the factor, $R\tau/L_0$, must be less than 0.5. In this expression, τ is the time at the end of the compression.

A number of types of EMGs can be constructed some being more suitable than others depending on the specific application being considered. The following is a brief description of the main types of EMG that have been used. More details can be found in [2].

Spiral Generators [2]

The spiral or helical generator, illustrated in Figure 17, has the advantage that it has a large initial inductance packaged in a small volume. The great length of the path traced out by the contact following initiation of the explosive gives rise to considerable flux loss. However, this loss is offset by the fact that the initial inductance is roughly proportional to the square of the number of turns and, therefore, the length. The turns near the input usually have a small cross section and are close together since they do not carry much current during the early part of the generator burn. At the output end, the turns are given a larger cross section in order to carry higher output currents.

The spiral generator has by far the best energy multiplication factor M of the various types of EMGs for a given volume owing to the large initial inductance. The spiral generator is often used as a booster stage for other generators.

Coaxial Generator [2]

This generator is basically a coaxial transmission line in which the inductance is changed either by imploding the outer conductor or exploding the inner conductor. In a typical generator, a ring of detonators at the input end initiates the jacket of explosive. The current is parallel to the generator axis and the flux lines encircle the inner conductor. It is usual to implode the outer conductor rather than explode the inner conductor. The final burn stage of a spiral generator is often very similar to that of a coaxial generator with an exploding armature. The core tapers up to a larger diameter at the output end to increase the current-carrying capacity. The losses are less than those of the helical generator, but its relatively low initial inductance compared to its volume makes it suitable only for low inductance loads requiring very large currents. The low initial inductance is usually offset by employing a booster generator.

Plate Generator [2]

The power output of the preceding generator types would be greatly improved if the entire length of the armature could be moved simultaneously. The inductance would decrease more rapidly in this case. The plate generator is such a modification. In this generator, a planar explosive initiation system is used to drive the plates simultaneously over their entire areas. It is possible to change the time variation of the generator inductance by changing the separation of the plates at the input.

8.1.2 EMG Development and Applications

To date, the development of EMGs has been carried out primarily by groups at Los Alamos Laboratories under the leadership of C.M. Fowler and in the Former Soviet Union at Arzamas-16, the city where the All-Russia Scientific Research Institute of Experimental Physics is, the Soviet Unions first nuclear weapons lab. Some of this work has been described in open literature publications. Following the collapse of the Soviet Union, these two groups have collaborated [3] on the development of EMGs and their scientific applications.

The prime interest of both groups initially related to the use of EMGs for the compression of plasmas. This work is related to the development of controlled nuclear fusion. More recently, EMGs have been used to investigate a number of other physical problems such as the measurement of the critical field of superconductors, soft x-ray generation, isentropic compression of materials and lightning simulation. The development of a battery powered, compact EMG has been described [4].

8.2 Technology Trends

The use of EMGs to drive a number of compact explosively driven RF munitions was disclosed by A.B. Prishchepenko in a paper that was delivered at the EUROEM Conference that was held in Bordeaux, France in 1994. In this paper, Prishchepenko described how these RF munitions might be used against a variety of military targets. This reported development of RF munitions raised concern and interest in the US and other nations. Dr. Ira W. Merritt presented [5] an assessment of the significance of these developments to the Joint Economic Committee of the US Congress 1998.

Carlo Kopp [6], a Professor at Monash University in Australia, has published papers of the design of RF weapons and their potential effects.

8.3 Research and Development Opportunities

There are an increasing number of military applications that are going to require a high power, pulsed source of energy. These future applications include: electromagnetic guns, directed energy weapons, including high power microwave and NNEPM, and reactive armor. Development of these military technologies will be dependent, in many cases, on the development of suitable pulsed power sources. This is especially true of compact devices such as those needed for the incorporation of these technologies into warheads and munitions.

The military technology areas described are, in general, highly classified. In order to properly assess the threat that these technologies pose to future CF operations, conduct of research in this area is important. For this reason, the NNEMP and pulse power work being carried out at DREV, NRC and DREO under the TIF program should be continued and possibly expanded.

9 ENGINES

9.1 Diesel Engines

The Diesel engine has reached technological maturity in the last decade. Recent and near term activities on engine development will mainly concentrate on pollution and cost reductions. The state of art electronic engine has incorporated electronics and electronic-hydraulic fuel injection, advanced sensors, sealed electronics and firmware in the engine management system. The electronic engine has improved fuel efficiency and reduced pollution by more closely regulating the fuel injection and timing. Much work is still underway to incorporate ceramic material for the piston crown and values to allow hotter engine combustion to reduce pollution. There are also initiatives underway to incorporate exhaust gas and combustion blow-by recirculations, noise reduction, combustion air oxygen enrichment, variable geometry turbocharger, higher fuel injection pressure, and lower sulfide diesel fuel tolerant technologies (from current 500 ppm to 15 ppm in 2007 [1]) to further reduce pollution. Cummins, New Holland and IVECO have recently formed an European Engine Alliance that is jointly developing a new series of diesel engines that will be more fuel efficient and environment-friendly. Caterpillar, the diesel manufacturer for the CF Light Armored Vehicles (LAV III) fleet, claimed to spend more than US-$ 3M each working day to improve technology to increase product performance and environmental friendliness [2].

9.2 Gas Turbines

There are basically two types of gas turbines used for military applications, namely propulsion turbines for jets, battleships and main battle tanks, and utility turbines for co-generation of electricity, heat and compressed air. The technology development on these turbines is mainly driven by the original equipment manufacturer concentrating on pollution and cost reductions. Much effort is devoted to improve waste heat recovery, system reliability, multi-fuels capability, high temperature sensors, and the balance of plant efficiencies. Experiment is also under way to test the impact and effectiveness of operating gas turbines with hydrogen and hydrogen-rich fuels. Higher temperature blade tips and liners, better bearings, lower production costs and better environmental-friendliness are some of the challenges being addressed by manufacturers to make gas turbines a more competitive prime mover for non-aerospace applications. State-of-the-art solar turbine claims to achieve thermal efficiency of greater than 40% with very low NO_x emissions[2].

10 POWER MICROELECTROMECHANICAL SYSTEMS

The field of microelectromechanical systems (MEMS) has its origin in the integrated circuit (IC) industry. Using the silicon micromachining techniques developed for the IC industry, a variety of microsensors and micro actuators have been fabricated [1] and some are in commercial use (e.g. air bag activation). The next step in the development of MEMS technology is to merge the functions of compute, communicate, sense, actuate and control. Successful development of integrated MEMS devices will change the way people and machines interact with the physical world and will have a major impact on military technology.

10.1 State-of-the-Art

10.1.1 Overview Of MEMS Technology

Integrated MEMS will provide the advantages of small size, low power, low mass, low cost and high-functionality and will impact systems both on the micro as well as on the macro scales. In general, MEMS devices will be successful in applications where size, weight and power must decrease simultaneously with an increase in functionality. MEMS devices can be produced at low cost when produced in high volume.

Many of future military needs for increased performance, reliability, robustness, lifetime, maintainability and capability of military equipment can potentially be met by the use of MEMS devices in micro and macro systems.

Some of the potential military applications for MEMS devices include use in:

- Inertial measurement units for munitions, military platforms and personal navigation;
- Distributed control of aerodynamic and hydrodynamic systems;
- Distributed sensors both for condition-based maintenance and for structural health and monitoring;
- Distributed unattended sensors both for asset tracking and for environmental/security surveillance;
- Non-invasive biomedical sensors;
- Electromechanical signal processing.

10.1.2 Power MEMS

At the present time MEMS devices are powered almost exclusively by macroscopic power sources. The use of a single macroscopic power supply to power a large number of micro sensors or actuators causes a number of problems. One of the main problems caused by the use of a macroscopic power supply is an interconnect problem. Distribution of power from a central source causes problems [2] with layout efficiency in the silicon wafer and with electrical noise as a result of stray capacitance and cross talk between power and signal lines. In addition, there is a problem in controlling the power that is delivered to individual components.

To optimize the usefulness of MEMS devices, the next step in their development is to integrate a micro power source with the other MEMS components (micro actuator, micro sensor and IC electronics). This alternative would enable the development of a truly integrated system that communicates through information exchange only rather than through exchange of information and power. In addition, the use of a micro power supply for each

MEMS device permits local control of the power to each component thus reducing control system complexity. Other advantages should include lower noise, power efficiency and speed of operation.

Because of these potential advantages, DARPA [3] has recently sponsored the development of a number of micro power sources for MEMS use. The thrust of this development has been to use micromachining techniques to manufacture the micro power sources and integrate them with the other MEMS components. Systems that are being developed include micro batteries, micro fuel cells, micro photovoltaic sources and micro engines. In the following sections we provide an overview of work that is being carried out in this area.

10.1.3 Micro Power Source Basics [2]

In general, a micro power source will consist of three basic components. These components are:

a) a prime source of energy,
b) an energy converter and
c) an energy storage device.

The prime source of energy may take many forms. Ideally this source is available in the environment, for example as solar, thermal or kinetic energy, so that the energy can be "harvested" from the environment and does not need to be supplied. It may be, however, that this energy source is a fuel, such as hydrogen or propane, which needs to be supplied to the converter.

The energy converter takes the prime source of energy and converts it into the form that is needed, most commonly electrical energy. A solar cell, for example, converts the electromagnetic energy from the sun directly into electrical energy and a fuel cell directly converts the chemical energy of the fuel into electrical energy. Clearly some converters, such as micro engine generators, may be more complex and involve more than one energy conversion step (chemical to mechanical to electrical). The most important parameters that characterize the energy converter are size and energy conversion efficiency.

The energy storage device is not necessarily required if the energy source is continuous and the power demand is constant. Energy storage is often useful and can serve a number of functions however. For example, energy storage can allow energy to be accumulated over a long period of time and then delivered rapidly to a load. This allows the output power to be significantly higher than the average input power level for a short period of time. An energy storage device is also useful for smoothing out fluctuations in the energy supply. The most important parameters that characterize an energy storage device are charge/discharge rate and energy density.

10.1.4 Microfabrication Basics

Silicon micromachining [1] is a relatively new approach that is being used for the fabrication of micro power sources with dimensions on the µm scale. The technique is based on the use of process technologies that have been developed by the microelectronic industry. By combining the lithographic processing techniques of the microelectronic industry with other techniques for etching trenches and grooves into silicon wafers low cost micro power sources can potentially be fabricated.

Silicon micromachining can be divided into two general classes: bulk micromachining and surface micromachining. In the former, the silicon wafer is structured while, in the second, the sensor is fabricated on the surface of a silicon wafer. Key processes involved in silicon micromachining of power MEMS devices include:

10.1.4.1 Etching

Etching is a widely used technique for the fabrication of silicon microstructures. A wide variety of etchants are available for silicon. They can be wet or dry and enable silicon to be etched both isotropically and anisotropically. Anisotropic etching of silicon is based on the fact that the etching speed can vary greatly amongst the different crystal planes of silicon.

10.1.4.2 Bonding

Several techniques are available for bonding silicon wafers together during the fabrication process. These include: direct bonding of highly polished wafers by heat treatment, anodic glass to silicon bonding, low temperature glass bonding etc.

10.1.4.3 Film deposition

A variety of methods can be used for the deposition of thin films onto a silicon surface. These include spin casting for polymer films, evaporation and sputtering for metal and oxide films, and chemical vapor deposition.

10.2 Technology Trends

10.2.1 Micro Batteries

The development of MEMS for use in applications such as accelerometers, aerodynamic boundary layer control, movement sensors and micro optics will, in many cases, require a source of autonomous power. Micro batteries can provide an efficient and flexible method of providing such power. Micro batteries need to be small in size so they can be integrated with the MEMS device and they also need to have high power and energy densities. The battery must have sufficient capacity to meet the energy demands although capacity requirements can be minimized if the battery is coupled with an environmental source of energy such as solar, thermal or kinetic. Energy can be scavenged from the environment during off-duty periods and stored in the battery for use later on. Several groups have been actively developing micro batteries and a summary of this development is reported below.

A research group at Brigham Young University in partnership with Bipolar Technologies Corp. has developed [3-5] a micro battery based on the Ni/Zn couple and an aqueous KOH electrolyte. This battery has been built using IC microfabrication techniques. The completed micro battery has a thickness of less that 100 μm. Micro batteries have been fabricated that have current densities as high as 12 mA/cm^2, a voltage of 1.5 V and a capacity of 290 mC/cm^2. The following is an outline of the steps used to fabricate the battery on top of a silicon substrate.

1. A thin SiO_2 layer is grown thermally on the silicon substrate. This electrically isolates adjacent cells.
2. A Ti/Ni film is evaporated onto the SiO_2 layer. This metallic layer is then used as a base to electroplate the active nickel electrode (NiO-OH).

3. A photosensitive polymer layer is spin deposited onto the nickel electrode and the electrode material is patterned.
4. A polyimide layer is spun onto the wafer and cured. A Zn layer is then evaporated onto this polyimide layer.
5. A photoresistant layer is then deposited and the Zn layer is patterned.
6. The patterned Zn layer serves as a mask to plasma etch the underlying polyimide to form a cavity between the two electrodes.
7. The cavity is filled with KOH electrolyte and the cavity sealed using a laminating polymer to form the micro battery.

In addition to the Ni/Zn micro battery, the same researchers have also fabricated [4] a lithium-ion micro battery using a synthetic graphite anode and doped spinel cathode. This couple has a cell voltage of almost 4 V and higher capacity. As before, IC microfabrication techniques were used for battery fabrication.

A group at Sandia National Laboratories [6] has reported the development of lithium-cobalt oxide microbattery. In their work, a three-dimensional honeycomb structure was etched into a silicon substrate using deep reactive ion etching. The honeycomb structure formed by this etching process is shown in Figure 19.

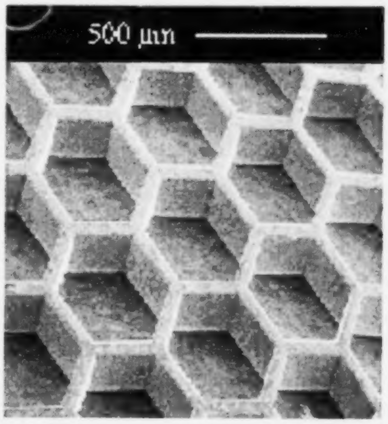


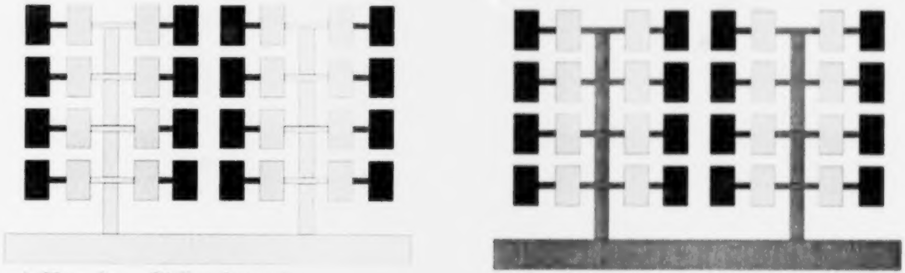
Figure 19: Micromachined Electrode Reservoirs (from [6])

The honeycomb pattern etched into the silicon serves as reservoirs for the electrode materials. In their battery, once an SiO_2 layer was formed, a carbon layer was deposited as a current collector and then the cavities were filled with the electroactive materials - in this case carbon and lithiated cobalt oxide. In this case the battery is formed in the discharged condition and then charged once assembled. This avoids having to handle reactive lithium metal in the fabrication process.

A NASA supported group at Caltech and UC Irvine [7] and a group at the Oak Ridge National Laboratory [8] are also doing work on the development of micro lithium batteries.

10.2.2 Micro Fuel Cells

As mentioned in the previous section, one of the main disadvantages of the microbatteries is the limited energy that each micro battery can store. This severely limits the duration that the battery can provide power to a MEMS device before recharge is necessary. Unlike batteries, fuel cells are not energy storage devices but are energy converters. Provided fuel (usually hydrogen) is fed to the fuel cell, the energy that can be produced by the cell is essentially unlimited. Schematics illustrating the provision of power to a sensor array using a rechargeable micro battery system and a fuel cell system are shown in Figure 20 respectively. In the case of the micro battery system, it has been assumed that the batteries are recharged from a central photovoltaic source. It is seen that, in this configuration, electrical interconnect to each battery is still required for recharge. With the fuel cell (Figure 20b), the electrical interconnects are replaced by gas (fuel) distribution channels which can be etched into the silicon substrate. Because these channels are non-conducting, the electrical noise and cross-talk problems that were discussed in section 1 do not occur.



a) Charging of Microbatteries

b) Fuel Supply to Micro Fuel Cells

Figure 20: Provision of Power to a Distributed Micro Sensor Array

Under DARPA sponsorship, a group at Case Western University [9,10] is developing a polymer electrolyte based micro fuel cell that would use hydrogen as a fuel and air. This fuel cell is being designed so that it can be fabricated using silicon microfabrication techniques. It is intended that the fuel cell operate in a passive mode without the need for active control of the temperature, humidity, reactant pressure or flow rate. Operation in a passive mode will simplify construction but result in lower power density than could be obtained with active control. The cross-section of a three cell CWRU micro fuel cell is illustrated in Figure 21.

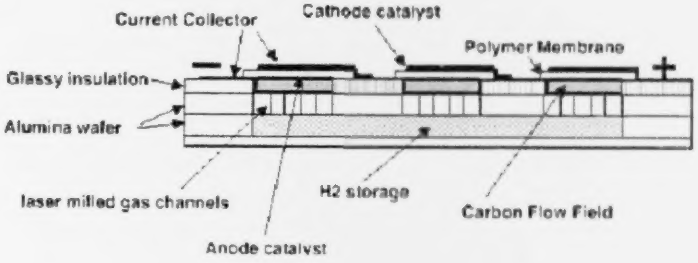


Figure 21: Cross-section of a CWRU Micro Fuel Cell (from [9])

One of the main problems that needs to be resolved for successful development of a passive micro fuel cell is improvement of membrane conductivity under low humidity conditions. Alternative membranes to Nafion are being investigated.

Other groups known to be carrying out the development of PEM micro fuel cells include Southwest Research Institute [11], Sandia National Laboratories [12], Lucent Technologies [13,14] and the University of Minnesota [15,16]. Work on a MEMS regenerative fuel cell is being carried out by Dynacs Engineering Co. and B.F. Goodrich Ltd. under NASA sponsorship [17].

10.2.3 Micro Engines

Micro engines have also been developed for providing power to MEMS devices. In one development, the University of California, Berkeley has developed [18] a MEMS rotary internal combustion engine (Figure 22). The goals of this project are "to develop and fabricate a mini and micro, internal combustion engine that uses a rotor/housing assembly to generate power from liquid fuels. The project will incorporate existing technologies and materials developed in the MEMS field and will require advanced internal combustion configurations. The project also aims to theoretically model those aspects of the engine operation that are uncertain due to the scale of the respective processes". To date a mini engine has been built with plans to develop a micro engine.

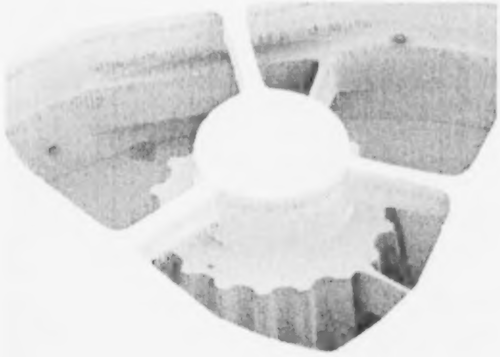


Figure 22: MEMS Rotary Internal Combustion Engine (from [18])

Honeywell Technology Center are pursuing [19] the development of a free-piston knock engine (Figure 23). The goal of this project is "to demonstrate a microscale autoignition internal combustion engine and generator that operates on hydrocarbon fuels, such as propane, butane or diesel, and delivers 5~10W/cm3 electrical power for soldier power and other battery applications".

One of the major problems associated with the development of micro engines is the development of micro combustion systems. In small systems, heat loss to the walls becomes a much more significant problem and combustion may be hard to sustain. Catalytic combustion may be a possible solution to combustion difficulties.

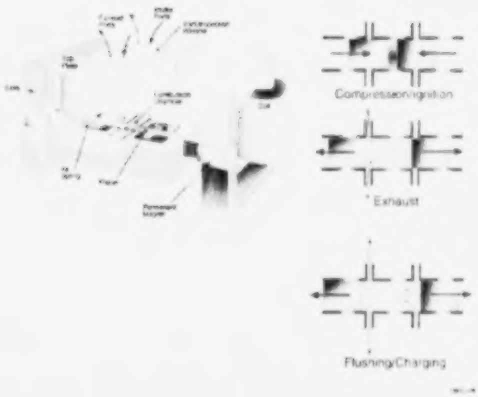

Compression/ignition
Exhaust
Flushing/Charging

Figure 23: MEMS Free Piston Knock Engine (from [19])

10.2.4 Micro Thermoelectric Generator

Recent effort has resulted in the development of microelectronic thermoelectric generators such as that illustrated in Figure 24. Note in this device that the height of the thermoelectric elements is only 1 μm. Techniques for the manufacture of microthermoelectric devices have been developed [20] that allow microelectronic machining techniques to be used for fabrication thus allowing easy integration of the power source with other electronic and sensor components.

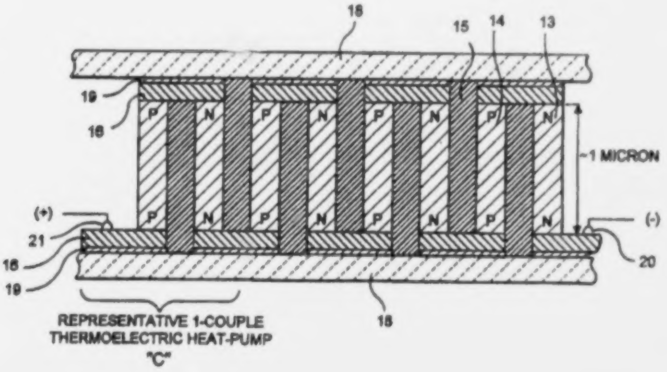

18
15
14
13
19
18
P
N
~1 MICRON
(+)
21
18
19
(-)
20
18
REPRESENTATIVE 1-COUPLE THERMOELECTRIC HEAT-PUMP "C"

Figure 24: Micro Thermoelectric Element (from [20])

Under DARPA sponsorship, the University of Southern California (USC) is developing [21] a micro TEG. The goal of the USC project is to "to develop a highly-miniaturized, integrated, monolithically and batch-fabricated power generator with no moving parts, capable of powering MEMS devices. The microgenerator will be based on the combustion of readily-available fuels such as butane, and will be produced using USC's EFAB (Electrochemical Fabrication) 3-D microfabrication technology".

As with micro engines, one of the major problems that may be encountered is the development of micro combustion systems. Work is being carried out at the Massachusetts Institute of Technology [22] to develop micro combustion systems that would be suitable as a heat source for micro TEGs.

The use of micro thermoelectric devices to harvest thermal energy from low-grade environmental heat sources appears to be attractive for some MEMS applications.

10.2.5 Micro Photovoltaic Systems

The harvesting of electromagnetic energy that is available from the sun or from interior lighting is attractive for powering MEMS devices. Under National Science Foundation sponsorship, a group at Georgia Tech has developed [23] a high voltage solar cell array for powering an electrostatically driven micromachined silicon mirror. The solar array is based on hydrogenated amorphous silicon elements. A single photo cell consists of a triple amorphous silicon layer (p-I-n/p-I-n/p-I-n a-Si:H) and produces an open circuit voltage of 1.8-2.3 V and a short circuit current of 2.8 mA/cm^2 for AM 1.5 radiation. In the system developed 100 cells were interconnected to give an array voltage of 150 V. This high voltage was needed for electrostatic deflection of the silicon mirrors. For many applications, 2 or 3 cells would be sufficient.

10.3 Research and Development Opportunities

The following are potential research opportunities that have been identified in the power MEMS area:

a) Development of Micro Batteries. It appears as if many micro sensor and actuator applications will need to incorporate a micro battery to provide autonomous power. For short term, low power applications, a micro battery may have sufficient capacity to act as a stand-alone power source. In many applications, however, the prime source of energy may be an environmental source such as solar or thermal energy. In these cases, it can be anticipated that a micro battery will still be included to provide storage capacity when the environmental source fluctuates, to meet peak power demands and to smooth power fluctuations.

Because of its potentially high energy density, work in this area should concentrate on the development of lithium micro batteries. Polymer or solid electrolyte systems appear particularly attractive because of their compatibility with micro fabrication techniques. A multi-disciplinary research group that consists of experts in both the microfabrication and battery electrochemistry area is needed to carry out this project. Canada has strong expertise in both areas both in Industry and University to initiate such a project. This area of research has potential commercial applications as well.

b) Development of Micro Fuel Cells. An advantage that fuel cells have over batteries is that, in a fuel cell, the power and energy requirements can be decoupled. For long periods of operation, the energy density of the fuel cell approaches that of the fuel that can be very high. The fuel cell will provide power as long as it is fed fuel.

With an array of fuel cell powered sensors, a central source of fuel could be used with the fuel being fed through micro channels etched into the silicon substrate. These channels are non-conductive so problems with electrical noise induced by cross talk and electromagnetic interference that are encountered when electrical interconnects are used are avoided. Integration of the sensor/actuator and the power source also means that much higher operating speeds are potentially possible. This will be a major advantage as the clock speeds of micro electronic systems increase.

Solid polymer electrolyte systems appear particularly attractive because of their compatibility with micro fabrication techniques and low temperature of operation. A multi-disciplinary research group that consists of experts in both the microfabrication and fuel cell electrochemistry area is needed to carry out this project. Canada has strong expertise in both Industry and University to initiate such a project. This area of research has potential commercial applications as well.

c) Development of Micro Thermoelectric Generators: The scavenging of thermal energy from the environment may provide a means of powering low power, distributed sensors. In general, the temperature of available sources and sinks will be low. The development of low temperature, micro TEGs is worth consideration. Significant progress in raising the figure-of-merit of TEG materials is being made.

A multi-disciplinary research group that consists of experts in both the microfabrication and TEG area is needed to carry out this project. Global Thermoelectric gives Canada world-class expertise in the TEG Industry.

Renewable Energy Sources

11 SOLAR

11.1 Start-of-the-Art

Solar Energy is a renewable resource that will have increasing military interest. Solar energy is free and can be harvested by using photovoltaic panels, coolant panels, and black body mass. For the military, coolant and black body solar collectors have limited applications whereas photovoltaic (PV) technology will be of increasing importance.

The present technology mainly consists of rigid and fragile crystalline silicon cells with energy conversion efficiency ranging from 15-23% in 25°C ambience. A higher ambient temperature will either cause a reduction in power output, or product life. Photovoltaic panels can either be a stand-alone unit, or in a solar farm where reflective concentrators are used to focus the solar ray onto the panels for increased efficiency. Due to low energy conversion efficiency and crystalline rigidity, present technology is more suited for fixed installation where a large surface area and an optimum solar angle are available for harvesting useful quantities of energy.

As the military increases its use of portable electronics, and with more deployments near the Equator region, solar power can become a viable alternative to primary batteries and thermoelectric generators. The canvas bonded small solar panels, when unfolded and placed at a suitable exposure angle, can provide adequate output capacity to charge tactical voice and data communication devices. Solar power can also be used to reduce O&M cost by extending the life of vehicular batteries through sulfation reduction when the vehicle is parked for an extended period. Solar power can also increase soldier's comfort by powering micro-ventilators in the helmet and clothing. Development is also underway to integrate solar panel, charging circuit, and batteries on a family of land mine detectors to extend deployment time, reduce battery usage, and improve logistic support in rural mine clearance areas. Proper packaging of the solar panel for logistic transport and field deployment can improve their viability for use in UN and CF peace keeping deployable camps, signal towers and guardhouses.

11.2 Technology Trends

The future battle frontier will involve the use of land and airspace robots (UAVs). These robots can be economically produced (when compared to a soldier!), and fitted with sensors and munitions for defensive or offensive deployment. The robots can be used as bio-chemical agent sentry detector, seismic-ground movement detector, lethal or non-lethal area access denial system, or a signal relay station, etc. These robots can stay in silent watch indefinitely when fitted with solar cells, regenerative fuel cell and energy storage technologies. The solar cell technology can be embedded or molded to conform with the shape of the robots or military equipment. It would produce electricity to energize the host platform, extra electricity to charge the batteries or to produce hydrogen via the regenerative fuel cell. Under low solar condition such as nights and cloudy days, the batteries, or the regenerative fuel cell would energize the host platform.

11.3 Research and Development Opportunities

The current technology is not suitable for tactical applications due to its fragile crystalline structure and low efficiency. New nano-crystalline solar cells with thin film substrate, super-conducting interconnections and fault-tolerant micro-size integrated power management technologies are required to increase the energy harvesting efficiency, improve survivability, and reduce mass. Bio-organic and semiconductor type photonics technologies with high photovoltaic efficiency under low light conditions should be developed to extend the power generation effectiveness in cloudy days or shaded areas. Thin film, flexible, moldable, and survivable, high efficiency, wider wavelengths, and lower mass solar cells are extremely useful when coupled with micro-batteries or regenerative fuel cell. These types of advanced power sources can be fitted on soldier helmet and web kits to turn passive apparels into an integrated power suite. It can also be fitted on all combat platforms where energy harvesting is suitable.

To increase the lethality and longevity of the weapon platforms, there will be a need to further increase power density, preferably with solar power because it is the most abundant renewable energy source available. Solar power will be extremely critical for powering airborne micro-sensors, defensive and offensive UAVs for extensive mission duration. One of the means of achieving this is to deploy solar array satellites in high geo-synchronous orbit (i.e., 36,000km above earth) where these satellites will collect the solar energy, and beam the energy to the battle zone via microwave, millimeter wave, and optical/laser wavelengths. This type of wireless power transmission can effectively increase the solar cell (wideband receptor) effectiveness 24 hours a day and increase the cell efficiency by many folds. Such type of solar space station can provide adequate energy to energize/charge the robots, UAVs, command and controls suites in the battlespace with either visible or invisible wavelengths. This technology can also be used to illuminate (visibly) the enemy territory by beaming down with suitable wavelengths that can interact with munitions vapor (battlefield contaminants) in the enemy area.

Wireless power transmission and integrated high efficiency photovoltaics are disruptive technologies that will enable greater capabilities in future warriors and robotics warfare. The Canadian Space Agency and NASA [1] are considering the concept of deploying solar power satellites as a solar energy harvesting system for earth. The military can capitalize on such an initiative and therefore focus its new solar power system R&D on compact, flexible and moldable, thin film, wide bandwidth solar cells and integrating them with regenerative fuel cell and energy storage technologies for the battlespace.

12 HYDRO & TIDAL POWER

12.1 State-of-the-Art

Hydro and tidal power is the energy harvested from water movement. Electrical energy is harvested when water pressure propels a water turbine alternator or flex strips of electro-sensitive membrane (Piezoelectric or similar). The amount of energy is proportional to the energy mass of moving water and the efficiency of the energy-harvesting device. Unless the military is deploying camps nearby a waterfall, or rapids, it would be difficult to harvest this energy effectively. Naval deployment in locations with significant tidal flow can capitalize on tidal energy by using tidal generators anchored to the seabed and harvesting energy from surface waves or tidal changes.

12.2 Technology Trends

US DoD DARPA is investigating new material technology that can generate electricity when the electro-sensitive material is flexing in water currents. Such energy harvesting technology could be used to energize unattended water borne sensors and markers, or land based sensors and micro-robots nearby the river. This technology can also be integrated into large oceanic floating platforms with the harvested energy beamed to the satellites and UAVs. Although this technology is intended for marine environments, it can also be used to harvest wind power when flexible thin films are formed into shapes of flags and wind cones.

12.3 Research and Development Opportunities

Hydro and tidal power technologies should be monitored under Technology Watch. The recommended strategy is to consider future collaboration once the concept of electro-sensitive thin film generator technology has demonstrated its effectiveness in military applications.

13 WIND POWER

Wind is a renewable resource available only to selected geographical area. It is neither reliable nor environmentally quiet. The physical structure, rotor noise and the need for strong foundation required by large wind generator renders this technology more suitable for fixed installation in strategic camps and remote stations in temperate zones. This technology is not suitable for cold region deployment due to ice and snow loading on the rotors. Power requirement for a 400-man camp ranges from 250kW to 1000kw depending on ambient temperature and activity level. For efficient diesel generator operation, dedicated personnel would be required to add or remove generating capacity to match the power demand, which means multiple generators and personnel expenses. Installation of several 200kW solar panels and wind generators a short distance away from the camp, integrated with energy storage device can significantly reduce fuel requirement and run hours on the central power diesel generators. The present Canadian Forces deployable 300 kW and 500kW diesel generators, together with their central power distribution ISO, have adequate built-in features which will allow automatic generator start-and-connect-on-line, if solar and wind power is inadequate.

In an effort to reduce global warming and to increase utilization of renewable energy, wind power harvesting technology has advanced significantly in the last 10 years and the technology will be continuously refined. The Netherlands, Germany, Denmark, United Kingdom, India, and USA are world leaders in wind power with total installed capacity in excess of 14,000 MW. This is a growing industry supported both by commercial and governmental ventures, thus military R&D investment on the technology is not warranted. However, simulation and technology demonstration projects on UN camps, that have suitable wind and solar conditions, should be conducted to evaluate the potential O&M savings. The "egg beater" windmill technology developed by National Research Canada is worth considering for UN Camps.

Regarding tactical deployments, mini-wind generators, ranging from 100 W to 1000 W, are suitable for powering tactical airfield sensors, runway lighting, air traffic control stations and helicopters landing light systems, etc where noise and wind are acceptable elements. When properly sized, wind generators combined with solar panels and energy storage devices can provide adequate "remote power" to energize airfield lighting, monitoring and sentry defence systems.

14 NUCLEAR FISSION

Compared to fossil and solar energy, nuclear power is characterized by an extremely high mass and volumetric energy density. As an example, the fission of 1 gram of U-235 has equivalent energy to the burning of 1.3×10^6 grams of Diesel fuel. In addition, unlike combustion, there is essentially no emission from the fission process. On the negative side, reactor construction involves high initial capital cost, requires a long lead-time for construction largely because of regulatory hurdles and requires heavy radiation shielding for safety. The disposal of radioactive waste and decommissioning of reactors at the end of life remain contentious public issues.

14.1 State-of-the-Art

14.1.1 Background

Nuclear reactors have been extensively used for central power generation. In Canada, Atomic Energy of Canada Limited has developed the CANDU class of nuclear reactors that has the advantage that low enrichment fuel can be used. These reactors have been extensively sold to utility companies in Canada and throughout the world. A total of 30 CANDU reactors have been built or are under construction [1]. In Ontario, for example, approximately 30% of the electricity distributed by Ontario Hydro is generated from a nuclear source. In recent years, the use of nuclear power has been increasingly questioned by the public in Europe and North America because the disposal of nuclear waste remains an unresolved issue and operating and maintenance costs have been higher that originally anticipated putting some of the original economic projections in question. Some countries, such as Germany, are in the process of decommissioning the reactors they have built because of these reasons. This situation may well change however as global warming becomes more of a concern and the drive to reduce greenhouse emissions increases. A recent study has investigated the use of CANDU reactors for industrial purposes [2].

14.1.2 Small Nuclear Reactors and Military Applications [3]

A number of small fixed and mobile nuclear reactors have been built largely for military purposes. By far the largest numbers of these are the reactors that are used in nuclear powered submarines by many nations. The use of a nuclear reactor in this application provided essentially unlimited submerged endurance. In the US, seven small land based and one ship-mounted reactors were built for the US Army between 1954 and 1976. Several of these were designed for remote use and produced both heat and electricity. The reactors were designed to be transportable and to be suitable for rapid installation in remote areas. The total installed capacity of these reactors was 95 MW thermal and 18 MW electrical. The units ranged in size from 300 kW electrical to 18 MW electrical. All of these reactors were decommissioned in 1976.

A small reactor called SLOWPOKE was developed [3] by AECL for research purposes. This reactor was inherently safe and was licensed to operate unattended for up to 24 hours. Eight SLOWPOKE research reactors were installed starting from 1971 mainly in Universities for research and educational purposes. The SLOWPOKE research reactor was not designed as a source of thermal of electrical energy. In the 1980's, however, AECL undertook further development of the SLOWPOKE reactor to modify it to be a commercial source of heat and electricity. Within DND, studies were carried out to investigate the potential use as a heat and electrical source for CFB Alert and for submarine propulsion. For a variety of economic and social reasons, neither of these applications was pursued. Because of lack of market, AECL discontinued the development of the SLOWPOKE in the late 1980's.

During the same time frame, a joint Canada/US program was formulated to develop a "Compact Nuclear Power Source (CNPS). The schedule called for the installation of a demonstration reactor at Whiteshell Nuclear Research Establishment in 1988. The program was abandoned before these tests took place.

14.2 Technology Trends

No major trends to report.

14.3 Research and Development Opportunities

Initiation of R&D in this area is not recommended. The costs are very high and the number of applications is very limited.

15 NUCLEAR FUSION

Nuclear fusion is a reaction in which the nuclei of two light elements merge to form a heavier element. An enormous amount of energy is released in this process. The reactions of greatest interest for controlled nuclear fusion involve the fusion of deuterium either with itself or with tritium. Fusion energy offers the advantage that it offers a potentially inexhaustible supply of energy without the environmental drawbacks associated with the burning of fossil fuels or nuclear fission. Technically, however, it has proven to be extremely difficult to initiate and sustain controlled nuclear fusion since temperatures of about 100 million degrees K are needed to overcome the repulsive forces between the nuclei.

15.1 State-of-the-Art

The first program to produce power from nuclear fusion was initiated in the early 1950's and efforts have continued since that time. At the present time, the device that offers the greatest promise [6,7] for the development of a power producing fusion reactor is the Tokamak. For very short periods, up to 10 MW of power have been produced in a Tokamak through nuclear fusion. Considerably more work is required however before generation of power by nuclear fusion becomes economic. Because of the complexity of confinement at the extremely high temperatures needed for fusion, controlled nuclear fusion is only expected to be used for central power generation.

15.2 Technology Trends

No major trends to report.

15.3 Research and Development Opportunities

Work in this area is not recommended.

Energy Storage

The use of electric energy has many advantages: it is easy to use, safe, efficient and transformable in any other desired form of energy like mechanical energy or heat. It is easy to add, to divide and to distribute. Electric devices are easy to handle and to control. The major problem with electric energy is that it has to be there at the desired energy and power level in the moment of use. As for military purposes it can not always be generated in the moment of demand, so it has to be stored. As there is no "universal" storage for all purposes, the choice has to be made according to the characteristics of the application. Basically, energy can be stored mechanically like in flywheels, physically in the electric field of a capacitor or magnetic field of a coil. The basic storage still is mostly chemical: a fuel like gasoline or diesel or, in the mid- to long-term future, hydrogen. Batteries, which are also considered as a chemical storage, have been discussed earlier and will not further be mentioned here. The following sections give an overview on different types of storage and review their state-of-the-art and developmental potential.

16 MECHANICAL STORAGE

A rather efficient way to store energy mechanically is the use of a flywheel, especially with an integrated motor/generator unit. The energy itself is stored in the rotating mass of the flywheel's cylinder which is now mostly made of composite carbon fibers due to their strength and therefore capability to withstand the gyroforces at high rotating speeds.

Many companies manufacture flywheels, but not necessarily for mobile use or as a high energy storage. The following text describes a flywheel constructed by Magnet-Motor, Starnberg, Germany, which has been developed for civil use but can be adopted for military purposes.

16.1 State-of-the-Art

The Magnetodynamic Storage (MDS) is a flywheel storage unit with a vertical rotation axis. The rotor is a hollow cylinder primarily made of carbon fiber composite. For an optimum compact system design the motor/generator (M/G) unit is integrated inside the hollow rotor. The MDS gains stored energy while the M/G unit is run as a motor, accelerating the rotor. The MDS supplies energy back when the M/G unit is switched to generator mode, thus reducing the rotor speed.

The principle design of the MDS is presented in Figure 25.

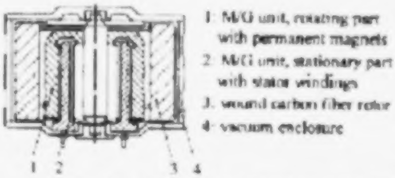

1: M/G unit, rotating part with permanent magnets
2: M/G unit, stationary part with stator windings
3: wound carbon fiber rotor
4: vacuum enclosure
1
2
3
4

Figure 25: Principle Design of MDS

For use in vehicles, the MDS is mounted in a housing with partially cardanic suspension in order to reduce the forces acting between the rotating MDS masses and the vehicle that is moving in the terrain, thereby tipping the MDS rotor axle.

The maximum permissible rotation speed of the rotor and its mass moment of inertia determine the energy capacity of the system. The power capability of the MDS is on the other hand set by the specifications of the M/G unit and the electronic system controlling the M/G unit.

The characteristic data of current MDS types available for applications in vehicles are summarized in Table 16.

Table 16: Current MDS types for mobile applications

		K3	K6	M1	
Stored Energy	E	7.2	21	32	MJ
Max. Power	P	150	450	900	kW
Operating Speed	n	12.000	21.000	18.000	min^{-1}
Diameter	d	0.66	0.66	0.78	m
Height	h	0.64	0.64	0.75	m
Mass	m	400	400	600	kg

MDS systems of the type K3 have been employed in electric urban transport buses since 1988, at a total of more than 200,000 operating hours up to now. The MDS systems K6 and M1 are further developed models, also for vehicle use, currently available as prototypes. In future military vehicles the MDS not only buffers energy for the weapon system but also can enhance the drive performance significantly. Various laboratory MDS units have been tested up to 80MJ and 5MW.

A flywheel is used for short to mid storage times. The self-discharge rate is lower than 0.5% per minute and still being improved. Flywheels are adequate intermediate storage for electric weapons, such as electric or ETC guns, as they can store enough energy for several shots and deliver enough power to quickly recharge the necessary pulse forming network for this application. They are also capable of providing sufficient energy for a certain time of silent watch in a tank and can increase the maneuverability of an All-Electric Combat Vehicle significantly.
Several developments have been made for the use in the civil markets, e.g. public transport.

16.2 Technology Trends

The possibility of higher rotating speeds can increase energy and power density of this type of storage. Therefore new materials that can withstand the gyroforces at high rotating speeds have to be developed and improvements in (permanent magnet) motor technology will keep this a promising storage technology.

16.3 Research and Development Opportunities

Their state-of-the-art is pretty mature and some types are readily available. so that mainly optimizations and ruggedization is needed for military use. Depending on the wish of applying this type of storage, DND could invest some minor amount of money together with the allies on adapting the storage to military requirements.

17 PHYSICAL STORAGE

Storing energy physically means to store it in either an electrostatic or electrodynamic field. Electrostatic fields of "normal" capacitors unfortunately contain only very little energy, but by using new materials the surface of the electrodes can be significantly increased and, therefore, store a much higher amount of energy. This new type of capacitor is called supercapacitor. In combining a capacitor electrode with a battery electrode to make a so-called battery capacitor (or batcap) one can achieve an energy density comparable to a battery.
Another method of physical energy storage is the magnetic field of a coil. In order to achieve sufficient energy densities, one has to use superconducting materials.

17.1 Supercapacitors and Batcaps

Supercapacitors (also called ultracapacitors and electrochemical double layer capacitors, EDLCs) have recently been introduced to the market. These are electrochemical power storage devices that store a charge using ions adsorbed at the surface of the electrodes. These capacitors can be cycled tens of thousands of times, unlike batteries. The electrodes can be of the same material, but they need to be high surface area. Carbon is usually used, which can have a surface area of 2000 m^2g^{-1}. Another material used is ruthenium oxide, but that is much more expensive. One of the leading researchers with this material is Professor Brian Conway of the University of Ottawa. The electrolyte in a supercapacitor can be aqueous (e.g. sulphuric acid or potassium hydroxide) or non-aqueous. The aqueous systems are normally limited to a maximum voltage of approximately 1.2V because of the decomposition of water at higher voltages. The non-aqueous systems can usually be charged to 2.5V to 3.0V. The energy stored in a supercapacitor is proportional to V^2, so the non-aqueous supercapacitors can store more energy. The main purpose of supercapacitors is to provide high power over a time period of up to approximately one minute. For this, they need to have a very low resistance, which means that aqueous systems may still be the better choice for a particular application, especially for low temperature. Small supercapacitors that could be used with portable batteries are presently being commercialized, but this is still a relatively new field for research. A possible area of research for DND is to make carbons with a variety of pore sizes in order to determine the optimum carbon for low temperature operation. This is not trivial because a lot of the surface area derives from small pores which are too small to support an electrochemical double layer and so do not contribute to the capacitance.

Supercapacitors are likely to see widespread use in the future, particularly in parallel circuit with a battery for pulsed power. The supercapacitor can also allow the use of a less expensive bobbin cell, rather than spirally wound. One example of this would be the lithium-thionyl chloride couple, where the spirally wound cell has passivation and safety problems, but the bobbin cells do not. Supercapacitors will definitely extend the running time of lithium-ion batteries at low temperatures and, probably, also the battery life, because the battery is subjected to less stress during pulsing. The exact way that a battery and supercapacitor are connected in parallel also needs to be investigated because the current distribution between the two components is dependent on the relative resistance of the two parallel loops and an additional resistance may be needed to lower intercomponent currents.

Recommendations for supercapacitor research
Small supercapacitors are already in mass production and will find application within the CF for pulse power. Research is still needed to optimize the low temperature performance, which may require an aqueous electrolyte, rather than the non-aqueous versions that are in production. Large supercapacitors may be used in electronic weapons. Because carbon is the cheapest material to use for

supercapacitors, it is suggested that DND carry out research aimed at optimizing the surface area and pore size distribution of carbon electrodes for supercapacitors. It is anticipated that this would entail collaboration between the DND groups at the NRC and the RMC.

17.2 Superconducting storage

17.2.1 State-of-the-Art

Superconducting Inductive Energy Storage

In Germany, superconductive energy storage has been investigated for use with an electromagnetic gun. The following sections describe the test equipment that has been used. For several reasons, including availability of funding, research on this topic is not conducted at the moment.

The multi-solenoidal design of a superconducting energy storage system is shown in Figure 26. The main data are summarized in Table 17. The superconducting power supply system consists of 6 identical sectors, each complete with storage solenoid, switch and charging device. These elements can be manufactured and tested individually.

The solenoidal coils, which are arranged in a hexagon, are energized with alternating magnetic field directions so that the total magnetic stray field to the outside is compensated to a high degree.

Table 17: Design of a Superconducting Storage

	Hexagon of 6 solenoid elements (parallel discharge condition)
Conductor	NbTi in a Cu matrix
Diameter / Height	590 mm / 540 mm
Weight	150 kg
Inductance	11 mH
Rated current	9,600 A
Max. B	5.6 T

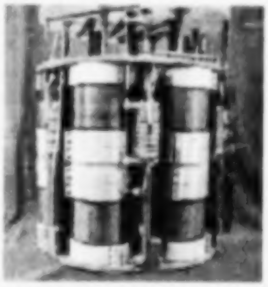


Figure 26: Laboratory SIPPS Set-Up

Superconducting Switches

Superconducting opening switches make use of a triggered very fast transition from zero to normal resistivity. This means, however, that for this type of opening switch the resistance is not infinite in the "open state", as it would be desired for an ideal switch. The achievable switching power is related to the quantity and to the characteristic data of the superconductor material applied. In order to keep the amount of material for the switch low, it is necessary that the conductor is characterized by high resistivity in the normal conducting state as well as by high current density in the superconducting state. These conditions in combination with the required dynamic performance are met well within the available LTS conductors by cabled wires of NbTi filament conductors in a CuNi matrix.

In the practical design the superconducting switch is composed of a long conductor arranged in a very-low-inductance configuration. The minimization of the inductance is essential for achieving fast switching performance and low switching losses. Another requirement for the superconducting opening switch is a high dielectric strength, which can be optimized by the geometrical design and the insulation materials applied.

The design data and characteristics of the switching components are presented in Table 18.

Table 18: Design Data of Superconducting Switch Element

Conductor	NbTi in a CuNi matrix
Diameter / Height	86mm / 450mm
Weight	7.5 kg
Inductance	9.5 µH
Rated current	2,000 A
R_{normal} (T=5K)	60 Ω
Triggering	current peak

17.2.2 Technology Trends

The currently available superconducting materials are so-called LTS (low temperature superconductors) which means that they obtain their unique superconducting properties only at very low temperatures of about 4 K, the temperature of liquid helium. This requires a big cryogenic effort.
Research is conducted to find so-called HTS (high temperature superconductors) which means they are already superconducting in the temperature range of liquid nitrogen. Yet, although some materials have been identified that have these properties, there are no ways to produce things like wires and coils from these highly porous ceramic materials.

17.2.3 Research and Development Opportunities

Superconducting storage is not yet an application for military use in the field. Until high temperature superconducting materials are available, the cooling efforts are too high and too complex. As proven by TZN Unterlüß, ETC guns can also be run by using a pulse-forming network of capacitors and switches. They also seem capable of satisfying the needs of HPM and laser weapons. DND should keep a watching brief on this technology but there is no need to invest money on it.

18 CHEMICAL STORAGE

As for the energy density, chemicals (fuels) store energy at a high level. Due to the limited speed of the chemical reaction that transforms the chemical energy into electrical energy, the power density level is rather low. The most commonly used chemicals for energy storage are liquid at ambient temperature and pressure (gasoline, diesel and jet fuel) and can be easily stored in tanks. The energy contained in these chemicals is usually turned into electric energy by being burnt in a combustion engine or in a turbine driving a generator.

Fuels that are gaseous at ambient conditions are not as easy to store because they need pressurized tanks but, for most gases, the technology is available. A common gaseous fuel is natural gas.

For environmental and other reasons, hydrogen is an alternative fuel to use, which should also see increasing use as petroleum deposits diminish. Hydrogen can be added to "normal" fuels where it can decrease the emission of pollutants by up to 40%. It can be burnt in a combustion engine, producing far less emissions than fossil fuels. A more elegant way of using hydrogen is in fuel cells, generating electricity to drive various electrical equipment. Most fuel cells operate only by being fed with pure hydrogen, hence, for widespread use of fuel cells (with their many advantages which have been described in an earlier section), the major problem to be solved is that of safely producing, distributing and storing hydrogen. With the increasing energy demands of the growing world population, it is believed that the only way to avoid a major energy crisis is to turn towards a hydrogen economy. Although it might take a few decades to become mostly independent from fossil fuels, the military should be aware of and be ahead of the commercial developments. The following paragraphs deal with the different ways and possibilities of providing the necessary hydrogen supply for future fuel cell applications.

18.1 Hydrogen Production

Although hydrogen is the universe's most abundant element, it doesn't naturally exist as a gas (H_2) on earth. It is always combined with other elements such as oxygen (H_2O, water) or carbon (methane (CH_4), coal, petroleum, etc.). Hydrogen is also found in all living matter – biomass. Therefore it can be produced from renewable energy sources and be part of a clean and elegant cycle being generated using non-fossil fuels. To produce hydrogen as a gas, several methods can be used. The choice of production methods will vary with the quantity and desired purity of the hydrogen.

18.1.1 State-of-the-Art

18.1.1.1 Hydrogen from Water

Electrolysis

Water can be separated into hydrogen and oxygen by passing a low voltage, direct current through it, whereby hydrogen is evolved at the cathode and oxygen at the anode. The hydrogen produced this way is very pure; the major impurities are oxygen and water. The purity can be easily enhanced through simple catalytic removal of the oxygen and subsequent drying.

Photovoltaic cells, or windmill generators, could produce the current used for the separation of water. This would make it a really renewable cycle. Depending on which source the electricity comes from, electrolysis is a rather expensive way of generating hydrogen. But, if hydrogen of high purity (and also the oxygen) is needed, this method is still worth consideration.

PEM-Electrolyzers

Proton Energy Systems™ has successfully demonstrated that its proprietary technology produces hydrogen directly, at a pressure exceeding 135 bar, from electricity and water without mechanical compression. This high pressure hydrogen generation technology is based on an advanced Proton Exchange Membrane water electrolyzer design and will enable on-site production of high pressure, high purity hydrogen suitable for fuel cell vehicle refueling or industrial cylinder refueling.

This principle is basically a regenerative fuel cell, which can be used either to produce electricity from hydrogen and oxygen, or to produce these elements from water when supplied with electricity. This could be very useful in combination with renewable energies like wind and sunlight.

Steam Electrolysis

Steam electrolysis is a variation of the conventional electrolysis process. Some of the energy needed to split the water is added as heat instead of electricity, making the process more efficient than conventional electrolysis. At 2500 °C, water decomposes into hydrogen and oxygen. The heat could be provided by a solar energy concentrating device. The problem here is to prevent the hydrogen and the oxygen from recombining at the high temperatures used in the process.

Thermal Watersplitting

A radically different approach has been investigated by the United States, Japan, Canada and France using temperatures of up to 3000 °C to split the water molecules. In 1996, the Weizman Institute in Israel experimented on this topic. As with the steam electrolysis, it is difficult to prevent oxygen and hydrogen from recombining at these high temperatures. Israel was experimenting with ceramic membranes, but there is no available information on that work, nor on any more recent research.

Thermochemical Water Splitting

Thermochemical water splitting uses chemicals such as bromine or iodine to split the water molecule into hydrogen and oxygen. The process is assisted by heat and usually occurs in three steps.

Photoelectrolysis

Photoelectrochemical processes use two types of electrochemical systems to produce hydrogen. One uses soluble metal complexes as a catalyst, while the other uses semiconductor interfaces. When the soluble metal complex dissolves, the complex absorbs solar energy and produces electrical charge that drives the water splitting reaction. This process mimics photosynthesis. The other method uses semiconducting electrodes in a photochemical cell to convert optical energy into chemical energy. The semiconductor surface serves two functions, to absorb solar energy and to act as an electrode. Light-induced corrosion limits the useful life of the semiconductor. At present, experience in this process is minimal.

Biological and Photo-Biological (Sunlight Assisted) Water Splitting

These processes use algae and bacteria to produce hydrogen. Under specific conditions, the pigments in certain types of algae absorb solar energy. The enzyme in the cell acts as a catalyst to split up the water molecules. Some bacteria are also capable of producing hydrogen, but, unlike like algae, they require a substrate to grow on. The organisms not only produce hydrogen, but also clean up pollution as well.

Recently a mechanism to produce significant quantities from algae has been discovered. After allowing the algae culture to grow under normal conditions, it was deprived of both sulfur and oxygen, causing it to switch to an alternate metabolism that generates hydrogen. After several days of generating hydrogen, the algae culture was returned to normal conditions for a few days, allowing it to store up more energy. The process could be repeated many times. Producing hydrogen from algae could eventually provide a cost-effective and practical means to convert sunlight into hydrogen.

18.1.1.2 Biomass

The production of hydrogen can result from high-temperature gasifying and low-temperature pyrolysis of biomass (feedstocks include wood chips plus forest, agricultural and municipal residues). This technology is currently available for fossil fuels.
The biomass is first converted into a gas through high-temperature gasifying, which produces a vapor. The hydrogen-rich vapor is condensed in pyrolysis oils and then can be steam-reformed to generate hydrogen. This process has resulted in hydrogen yields of 12%-17% by weight of the dry biomass.
Although, during this process, carbon oxides are emitted (e.g. gasifying of wood chips), this is a "clean" process because these carbon oxides were removed from the atmosphere during growth.

18.1.1.3 Reforming (Methanol, Hydrocarbon Fuels)

Reforming hydrogen from hydrocarbon fuels is not a non-polluting way of producing hydrogen. Problems also occur because of the required purity of the hydrogen, which makes cleaning processes necessary. It also decreases the overall efficiency of the fuel cell system and increases size, weight and cost. Still, this method can be considered as an intermediate step away from fossil fuels to a new hydrogen economy.

Natural Gas Steam Reforming
The first step of this two-step process is to expose natural gas to high-temperature steam, using its thermal energy to break up the chemical bonds. This involves the reaction of these fuels with steam on catalytic surfaces. In this step of the reaction, the fuel decomposes into hydrogen and carbon monoxide. The second step is a "shift reaction" to convert the carbon monoxide and water to produce additional hydrogen and carbon dioxide. These reactions occur at temperatures of 200 °C or higher. Most hydrogen is produced by this process. The yield of hydrogen is approximately 70 to 90%.

Methanol Reforming
Methanol is reformed in a similar process as natural gas. The advantage of using methanol is that it is liquid at ambient conditions and, therefore, can easily be stored and distributed. Methanol reformers are being developed by industry in different sizes for use in automobiles or in submarines. The main disadvantage of reformers is that they always add weight, volume and complexity to a system. The total efficiency decreases and the costs increase. To overcome the reforming and storage problem, industry is working on the direct methanol fuel cell as an intermediate solution.

Reforming of Other Hydrocarbon Fuels

A closer look at the chemical formulae of any fossil fuel reveals that hydrogen is present in all of the compounds. The trick is to remove the hydrogen safely, efficiently and without any of the other elements present in the original compound. Hydrogen has been produced from coal, gasoline, methanol, natural gas and any other fossil fuel currently available. Some fossil fuels have a high hydrogen-to-oxygen ratio, making them better candidates for the reforming process. The more hydrogen present, plus the fewer extraneous compounds, makes the reforming process simpler and more efficient. The fossil fuel that has the best hydrogen to carbon ratio is natural gas or methane (CH_4).

Some car manufacturers are working on gas and/or diesel reformers because they think that fuel cell cars will be more easily introduced to the market if they can be refueled through the existing gasoline infrastructure. Otherwise it is necessary to introduce new distributing infrastructures for either methanol or hydrogen. The problem with diesel or gasoline is that they have to be refined to be much cleaner (contain far less sulfur) as they actually are now. So, one still couldn't just pour diesel into ones reformer tank. Although in smaller amounts, there are still being harmful emissions produced during the reforming of hydrocarbon fuels. As for military logistics, it would be very advantageous to use a diesel reformer for hydrogen production, as diesel is already a logistic fuel.

18.1.2 Technology Trends

There are many ways to produce hydrogen from fossil and/or regenerative fuels. New ways will be discovered and developed. Even today's production facilities can produce sufficient hydrogen for the beginning market. A shortage in hydrogen production is not to be expected.

18.1.3 Research and Development Opportunities

Because industry and governments are aiming for a hydrogen economy for the civil markets, there is no need for basic research from DND. The only special thing for military applications is the diesel reformer for logistic reasons. There is a need for DND development on this item if the CF opt for making hydrogen by reforming logistic fuel.

18.2 Hydrogen Storage

There are many different ways of storing hydrogen, yet the perfect solution (high volumetric and gravimetric energy density, safe, lightweight and easy to handle) has not been found.

18.2.1 State-of-the-Art

Pressurized Tanks

New materials have permitted storage tanks to be fabricated that can hold hydrogen at extremely high pressures. At present, the cost of the tanks and compression are high, but the technology is available.

In September 2000, IMPCO Technologies achieved a mass performance record of 11.3% hydrogen storage by weight, the highest storage efficiency ever demonstrated. This new compressed hydrogen storage device operates at maximum pressure of 350 bar with a safety factor of 2.25.

Liquid Hydrogen

Condensing hydrogen gas into the more dense liquid form enables larger quantities of hydrogen to be stored and transported. However, converting hydrogen gas to liquid is costly and results in a net loss of about 30% of the energy that the liquid hydrogen is storing as the gas has to be cooled to 20 K (-253 °C). In this form up to 8 wt% can be stored.

Metal Hydrides

Various pure or alloyed metals can combine with hydrogen producing stable metal hydrides. The hydrides decompose when heated, releasing the hydrogen. Hydrogen can be stored in the form of a hydride at higher densities than by simple compression. Using this safe and efficient storage system depends on identifying a metal with sufficient absorption capacity operating under appropriate temperature ranges. Depending on the selected metal or alloy, the heat that is needed to release the hydrogen from the hydride is widely different. The total amount of hydrogen absorbed is generally 1%-2% of the total weight of the tank. Some metal hydrides are capable of storing 5%-7% of their own weight, but which is only released when heated to temperatures of 250°C or higher.

Metal hydrides offer the advantage of safely delivering hydrogen at a constant pressure. The life of the metal hydride storage tank is directly related to the purity of the hydrogen it is storing. The alloys act as a sponge, which absorbs the hydrogen, but it also absorbs any impurities introduced into the tank by the hydrogen. The result is that the hydrogen released from the tank is extremely pure, but the tank´s lifetime and ability to store hydrogen is reduced as the impurities are left behind and fill the spaces in the metal that the hydrogen once occupied.

The German Navy uses metal hydride storage on their first submarine U212, but it is supposed to be replaced by a methanol reformer for the other vessels.

Gas-on-Solid Adsorption

Adsorption of hydrogen molecules on activated charcoal (carbon) can approach the storage density of liquid hydrogen. The problem with activated carbons is that only a small fraction of the pores in the typically wide pore-sized distribution are small enough to interact with gas phase hydrogen molecules. Therefore only a few wt% can be achieved.

Up to now, good performance has been achieved at low temperatures. The behavior at room temperature is under investigation.

Nanostructures

Carbon single-wall nanotubes (SWNT) are essentially elongated pores of molecular dimensions and are capable of adsorbing hydrogen at relatively high temperatures and low pressures. This behavior is unique to these materials and indicates that SWNT are the ideal building block for constructing safe, efficient and high energy density adsorbents for hydrogen storage applications. In 1999, it was demonstrated that purified, cut SWNT adsorb between 3.5 wt% – 4.5 wt% hydrogen under ambient conditions in only several minutes and that adsorbed hydrogen is effectively "capped" by CO_2, making it stable for weeks in atmospheric conditions. The hydrogen can be released with small changes to temperature and pressure conditions.

This technology is considered to be a long-term solution, which still needs a lot of thorough research and development.

Microspheres

Very small glass spheres can hold hydrogen at high pressures, charged with gas at high temperatures, where the gas can pass through the glass wall. At low temperatures, the glass is impervious to hydrogen and it is locked in. Customized glass spheres are being developed for this purpose.

Microspheres have the potential to be safe, resist contamination, and contain hydrogen at a low pressure, which increases the margin of safety. The commercial spheres that DERA UK tested should have been able to withstand pressures of up to 680 bar, but most spheres broke at a pressure of 200 bar.

Chemically Stored Hydrogen

Hydrogen is often found in numerous chemical compounds. Many of these compounds are used as a hydrogen storage method. The hydrogen is combined in a chemical reaction that creates a stable compound containing the hydrogen. A second reaction occurs that releases the hydrogen, which is collected and utilized by a fuel cell. The exact reaction employed varies from storage compound to storage compound.

Some examples of various techniques include ammonia cracking, partial oxidation, methanol cracking etc. These methods eliminate the need for a storage unit for the hydrogen produced, because the hydrogen is produced on demand. One concept for hydrogen on demand production is the Powerball^{TM} concept [19], which is based on sodium hydride. Another concept by Millennium Cell, based on sodium borohydride (which DND is already investigating for the portable fuel cell), is introduced in the following paragraphs.

The Millennium Cell Concept [20]

Millennium Cell has invented, patented and developed a proprietary chemical process that solves the problems associated with generating, storing and transporting hydrogen by generating pure hydrogen gas from safe, environmentally friendly raw materials. This process, known as Hydrogen on Demand^{TM}, uses sodium borohydride ($NaBH_4$), a derivative of borax, to generate and store hydrogen. Borax, a chemical commonly used in laundry detergents, is found in substantial reserves globally. In Millennium Cell's proprietary process, sodium borohydride is combined with water to create a non-toxic, non-flammable aqueous alkaline solution that produces hydrogen on demand – that is, only when the solution is in contact with a metallic catalyst. When the sodium borohydride solution and catalyst are separated, the solution stops producing hydrogen. After being in contact with the catalyst, the fuel is spent and goes into a waste tank. This waste is recyclable into new fuel.

Millennium Cell's Hydrogen on Demand^{TM} technology has numerous advantages:

- It is compatible with the existing infrastructure for gasoline. After minor modifications, a modern vehicle can run on the Hydrogen on Demand^{TM} system. The sodium borohydride fuel used by the hydrogen generating system could be distributed through the existing network of neighborhood gasoline stations.
- The weight-energy ratio of sodium-borohydride is almost the equivalent to that of gasoline, meaning that sodium borohydride produces the same amount of energy per gallon of fuel as gasoline produces.
- The Hydrogen on Demand^{TM} system is convenient. Not only can it be used to produce hydrogen for direct use in internal combustion engines, but it can also be used to produce hydrogen for powering fuel cells. Every major auto maker is scheduled to have fuel cell cars available by 2006.

In addition to all these technical advantages, Millennium Cell's Hydrogen on Demand^{TM} is an ideal power source because the fuel is non-toxic, non-flammable, renewable and recyclable.

The system developed for car propulsion is based on the liquid water and salt solutions at room temperature, is easily accessed without energy input, is stable in air, is not too heavy and not too big. The Millennium Cell Hydrogen on Demand^{TM} generator uses the following chemical reaction.

$$\mathrm{NaBH_4 + 2\,H_2O \xrightarrow[\text{Catalyst}]{} 4\,H_2 + NaBO_2}$$

Sodium Borohydride, a salt, is dissolved in water where it stays until gaseous hydrogen is needed (left side of reaction). When hydrogen is desired, the sodium borohydride solution is pumped over a catalyst. The hydrogen gas comes out and leaves behind sodium borate ($NaBO_2$), another salt, which remains dissolved in water (right side of reaction). Without the catalyst, the hydrogen generation does not occur. Important points about the above chemistry are:

- The reaction is easily controlled via the catalyst and reactor configuration.
- Half of the hydrogen comes from the borohydride, the other half comes from the water.
- The catalyst can be reused many times.

The tank can be made out of plastic, molded to match the shape of an automobile chassis and will be essentially the same size as the standard gas tank. The rest of the system is reasonably compact. According to the ideas discussed above the fuel needs to be in contact with the catalyst. To accomplish this task in a car the fuel is pumped to a chamber containing the catalyst. The chamber releases all of the hydrogen from the borohydride in one pass, enough to power the car, and the remaining borate goes to a spent fuel tank. When hydrogen is no longer desired, the pump is shut off, isolating the catalyst from the fuel. By turning the pump on and off, the hydrogen flow is easily controlled. Increasing and decreasing the rate of pumping can also affect a much finer control of the hydrogen generation rate.

18.2.2 Technology Trends

Industry is working heavily on developing efficient and safe hydrogen storage and hydrogen production on demand. For introducing e.g. fuel cell vehicles to the market this is a basic condition.

Although the civil market will develop storage technologies with high intensity for its own needs, some military requirements will not be met by only buying COTS. Especially safety issues have to be considered as it is, e.g., not desirable and potentially dangerous to have a high pressure tank hit by a bullet or shell fragments.

18.2.3 Research and Development Opportunities

To accelerate the development of hydrogen storage, DND should invest some money in research on the storage methods that most likely serve them best in terms of efficiency, handling and safety issues.

Carbon Nanomaterials

Carbon nanotubes and their hydrogen storage capacity are still in the research and development state. Research on this promising technology has focused on the areas of improving manufacturing techniques and reducing costs as carbon nanotubes move towards commercialization.

Chemically Stored Hydrogen

This field of research comprises reforming technologies, the reaction of chemical hydrides and slurries. These technologies could provide hydrogen on demand in the battlefield at a safe level.

19 HYBRID POWER SOURCES

Hybrid power sources can be almost any combination of power generators and/or energy storage systems. These combinations are used to improve the performance of the overall system, to make up for weaknesses of one of the components or for basic requirements. Usually one will find a combination of a power generator and an energy storage system but it may also be advantageous to combine two generating systems, possibly with storage as a third component.

There are a vast variety of examples where system properties are improved by using hybrid power sources but there are no general solutions. Each application requires a hybrid system especially designed for its special purpose. The following examples are presented to give an idea about what can be achieved and how.

A typical example is the power system used in most vehicles. The system comprises the internal combustion engine with an electric alternator and the battery. In order to start the engine one uses the stored energy of the battery by using the alternator as a motor to make the engine turn and ignite the combustion. Once the engine is running it drives the alternator as a generator that restores the energy in the battery and supplies all electric loads with sufficient energy.

Batteries might also be used together with fuel cells to get the peripherals running on a startup. On the other hand fuel cells can serve to recharge secondary batteries, e.g. for use in applications where it might be impossible for several reasons to integrate a (micro) fuel cell directly. Batteries and fuel cells may also be combined in larger scale power systems such as in submarines for Air Independent Propulsion.

Another new combination is the use of batteries and supercapacitors. Supercapacitors in combination with secondary lithium-ion-batteries can solve the problem of poor low temperature battery performance.

Supercapacitors are also useful in vehicles as they can be charged and discharged rapidly. For this reason they can serve for recuperating braking energy and, on the other hand, for providing the high power for acceleration or slopes.

Flywheels are also very good partners in hybrid systems. In combat vehicles their power capabilities can improve acceleration and speed performance significantly. They also allow a longer time period of silent watch and are able to charge pulse-forming networks for high power electrical weapons. They have been used on public transport busses to provide emission free driving for a few kilometers in downtown areas.

Storage systems, such as flywheels or batteries, are also very useful in combination with renewable power sources such as solar and wind. The oversupply during daytime or periods with wind can be stored and used at times where demands cannot be fulfilled. Peak-leveling is another application. Renewable energy can also be used to produce fuel (e.g. hydrogen) for fuel cell applications.

Table 19 shows combination possibilities for several power sources and storage options.

Table 19: Possible Combinations of Hybrid Power Sources

	ICE	Fuel Cells	Batteries	Super-capacitors	Regenerative Power Sources	Fly-wheels
ICE				X		X
Fuel Cells	X		X	X		X
Batteries	X	X		X	X	X
Super-capacitors	X	X	X		X	X
Regenerative Power Sources	X	X	X	X		X
Flywheels	X	X	X	X	X	

Recommendations on hybrid systems

There are many possible hybrid configurations of power sources. These may be battery / supercapacitor, battery / fuel cell, battery / photovoltaic, and fuel cell / supercapacitor. Some of these are already in use, such as lead-acid / photovoltaic for remote power in the arctic. Although new technology tends to dominate the electronics world, there may still be a role for older technology to play. For both regular and emergency use, power for some radios, plus other low power devices, could be generated from a lightweight, integral, hand-cranked dynamo, and stored in a supercapacitor or a battery. The feasibility of this should be studied. From the point of view of research, the most important hybrid to investigate is battery / supercapacitor at a range of temperatures. There are no Canadian manufacturers of supercapacitors and the main thrust of research in industry is for electric vehicles, so no major collaboration is expected with industry. Exchange of information with CECOM and NATO partners is more likely. The level of effort required on hybrids has not been determined at this time and requires consultation with potential CF users.

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CHAPTER 4: ANALYSIS AND RECOMMENDATIONS

In Chapter 2 and 3 of this report, the main trends in military and power source technologies have been examined and specific power source requirements that the CF are expected to have in the future have been identified. In this chapter of the report, we assess the ability of the various power source technologies to meet these CF requirements, identify capability gaps in the technology and make recommendations for a future R&D program in advanced power sources.

1 ANALYSIS

1.1 Overview

An overview of the classification and characterization of the various CF power source requirements discussed in Chapter 2 is summarized in Table 20. To evaluate the ability of the various power source technologies to meet these future CF requirements and to identify the R&D opportunities, the procedure illustrated in Figure 1 (Chapter 1) was used. In this procedure, for each specific military application, all of the power sources are passed through a series of "filters" to assess whether the power source has the potential to meet the requirement and to select the most promising R&D opportunities. The main functions of these filters are to:

- Identify those power source technologies that have potential to meet the requirement;
- Identify technology gaps that exist and that require further R&D;
- Assess the capability of Canadian industry, governments and universities to conduct R&D in the technology area, and;
- Identify specific R&D opportunities.

In addition to these main functions, the "filter" process also examines specific technical, environmental and health issues that could influence the acceptability of the technology to the CF as well as identifying those areas where R&D is already being carried out by others and where DRDC support may not be necessary.

An indication of the ability of the different power source technologies that have been studied to meet the various requirements is given in Table 21. From this table, it is seen that, in general, there are several power source technologies that have the potential of meeting each of the requirements. The right hand row in Table 21 gives the total number of requirements that can potentially be met each power source technology. While this number is not necessarily indicative of overall R&D priority, it does give a good idea as to which technology areas have broad applicability and which are specific to only a few requirement areas. Technology areas such as fuel cells and chemical (hydrogen) storage stand out as having broad applicability.

As mentioned above, the "filter" process of Figure 1 has been used to identify R&D opportunities. The details of this analysis are given in Appendix 1. The results of this analysis are summarized in Table 22. For each requirement, this table identifies the power source options, Canadian capabilities in the technology area and R&D opportunities. Because of space limitations in the Table 22, the R&D opportunities are only presented in general terms. More detail is presented in the Appendix.

Table 20: Classification and Characteristics of CF Power Source Requirements

POWER RANGE	REQUIREMENTS	CHARACTERISTICS	POWER SOURCE OPTIONS
Micro Power (μW – 100 mW)	Sensors and Actuators	Microscopic scale High energy density/long endurance Environmentally friendly Energy harvesting desirable	Micro Batteries Micro Fuel Cells Micro TEG Micro TPV Generator Piezoelectric
Low Power (100 mW – 100 W)	Integrated Wearable Power	Extremely high energy density Highly efficient Low signature Safe and maintenance-free Low life cycle costs Energy harvesting desirable	DMFC Hydride Fueled PEMFC TPV Generator Micro Engine
	Portable Power	High energy density Compact/lightweight Low signature Non-polluting /low cost Long cycle life	Primary Batteries Secondary Batteries DMFC Hydride Fueled PEMFC
	Miniature Robotics	High energy density Maintenance free Low signature Reliable	Batteries Fuel Cells Microfabricated Fuel Cells TPV Generator Micro Engine
Medium Power (100 W – 100 kW)	Mounted/Mobile Power	Compact/lightweight Safe/easy-to-use Low fuel consumption Rugged/reliable Interoperability Continuous availability	Engine Generators Diesel Fueled SOFC PEM Fuel Cell Solar/Battery
	Aerospace Power	High energy density Compact/lightweight Reliable/safe	Secondary Batteries Primary Batteries Fuel Cells
	Remote Power	Highly reliable Low fuel consumption Maintenance-free Energy harvesting desirable	Solar Hybrid Systems Batteries Thermoelectric Generators
High Power (100 kW – 10 GW)	Vehicle Propulsion	High energy and power density Rugged/Safe Compact/lightweight Low fuel consumption Suitable for mil. environmental conditions Interoperability	Engines Diesel Fueled SOFC PEM Fuel Cells Hydrogen Storage Diesel Reforming Secondary Batteries
	Central Power	Low fuel consumption Low life-cycle costs Easy to use and to maintain Long MTBF, short MTTR Interoperability	Hydro Nuclear Magnetohydrodynamics Renewable Energy Sources
	Pulse Power	High energy and extremely High power density Compact Rugged	Mechanical Energy Storage EM Storage Explosive MCGs Piezoelectric Generators

Table 21: Capability of Power Source Technologies to meet Military Requirements

	Sensors/ Actuator	Integrated Wearable Power	Portable Power	Miniature Robotics	Mounted Power	Aerospace Power	Remote Power	Vehicle Propulsion	Central Power	Pulse Power	S&T Application Frequency
Electrochemical											
Primary Battery			X		X	X	X				4
Secondary Battery			X		X	X	X	X			5
Fuel Cell		X	X	X	X	X	X	X	X		8
Electromechanical											
Engine and Turbine				X	X		X	X			4
Piezoelectric	X		X							X	3
Thermoelectric		X	X	X	X		X				5
TPV		X	X	X	X		X				5
MHD									X		1
EMG										X	1
Power MEMS											
Micro Battery	X										1
Micro Fuel Cell	X										1
Micro Engine		X	X	X							3
Micro TE	X										1
Micro PV	X										1
Renewable Energy											
Solar	X		X	X		X	X		X		6
Wind	X						X		X		3
Water	X								X		2
Nuclear											
Fission									X		1
Radio Isotopic						X	X				2
Fusion									X		1
Hybrid	X	X	X	X	X	X	X	X	X	X	10
Energy Storage											
Electromagnetic			X					X		X	3
Mechanical								X		X	2
Chemical	X	X	X	X	X	X	X	X	X	X	10

Table 22: Analysis of R&D Opportunities

REQUIREMENTS	POWER SOURCE OPTIONS	CANADIAN CAPABILITIES			R&D OPPORTUNITIES
		Industry	Government	University	
Sensors and Actuators	- Microbatteries	X	X		- Micro Lithium Batteries
	- Micro Fuel Cells	X	X	X	- Solid Electrolyte Micro Fuel Cells
	- Micro Engines				
	- Micro Thermoelectric Generators	X	X		- Micro Thermoelectric Generators
		X	X		
	- Micro Photovoltaics				
Integrated Wearable Power	- DMFC	X	X	X	- Hydride Fueled PEM Fuel Cell
	- Hydride Fueled PEMFC	X		X	
	- TPV Generator	X		X	- Direct Methanol Fuel Cell
	- Micro Engine				- High Efficiency Generators
Portable Power	- Primary Batteries	X	X	X	- Lithium Batteries
	- Secondary Batteries	X	X	X	- Battery/Supercap Hybrids
	- DMFC	X	X	X	- PEM Fuel Cells
	- Hydride Fueled PEMFC				- Direct Methanol Fuel Cells
Miniature Robotics	- Batteries	X	X	X	- Hydride Fueled PEM Fuel Cell
	- Fuel Cells	X	X	X	
	- Microfabricated Fuel Cells				- Direct Methanol Fuel Cell
	- TPV Generator	X		X	- High Efficiency TPV Generators
	- Micro Engine				
Mounted Power	- Engine Generators	X	X	X	- PEM Fuel Cell
	- Diesel Fueled SOFC	X		X	- Direct Methanol Fuel Cell
	- PEM Fuel Cell		X	X	- High Efficiency TEG
	- Solar/Battery				
Aerospace Power	- Secondary Batteries	X	X		- Lithium Batteries
	- Primary Batteries	X			- Direct Methanol Fuel Cell
	- Fuel Cells	X			
Remote Power	- Solar Hybrid Systems	X	X	X	- Secondary Batteries
	- Batteries	X	X		- Thermoelectric Materials
	- Thermoelectric Generators	X			- Liquid Fueled TEGs

Vehicle Propulsion	- Engines	X			- PEM Fuel Cells
	- Diesel Fueled SOFC	X	X	X	- Ruggedization of Flywheels
	- PEM Fuel Cells	X		X	- Large, High Energy Density Supercapacitors
	- Hydrogen Storage	X	X	X	- Hydrogen Storage for Fuel Cells
	- Diesel Reforming		X		
	- Secondary Batteries				
Central Power	- Hydro	X	X		- Solid Oxide Fuel Cells
	- Nuclear	X	X	X	- Hydrogen Production from Logistic Fuels
	- Magnetohydrodynamics	X			
	- Renewable Energy Sources	X	X	X	
Pulse Power	- Mechanical Energy Storage	X			- High Energy, Pulse Power Source
	- Electrical Energy Storage		X		- Compact EMGs
	- Explosive Magnetocumulative Generator		X		- Explosive piezoelectric generators
	- Piezoelectric Pulse Generators				

1.2 Prioritization of R&D Opportunities

The purpose of the T^{3}R&O on Advanced Power Sources is to look at CF requirements out to the year 2020 and then use this information to help define future DRDC research in the advanced power source area. To achieve this it is clear that the future power source R&D program should target:

a) Those CF requirements that are viewed to be the most important, and;
b) Those where serious deficiencies exist at the present time.

Using this procedure, it is possible that some systems that have very high military priority may be given a low R&D priority strictly because existing or future COTS power sources are capable of meeting the requirement and further R&D is not necessary. For the development of a power source R&D program, ideally we want to identify requirements that are both operationally important to the CF **and** for which a serious deficiency in existing technology exists.

Using this information, the need to conduct R&D on the power source technologies has been prioritized taking into account the military requirements, the potential for the technology to meet the requirement, and Canadian capability to conduct an effective program. These technologies have been divided into three categories:

High priority areas: those where R&D need to be conducted.

Medium priority areas: those where R&D could be carried out if sufficient resources exist.

Low priority areas: where there is no need to carry out R&D.

Table 23 lists the various power source technologies that have been discussed in this report, broken down into the priority categories given above. Using this listing as a guideline, recommendations are made in the following section (Section 2) for the development of a research and development program to meet CF requirements out to the year 2020.

Table 23: Prioritization of Power Source Technologies

High Priority Technologies
Chemical storage (hydrogen production and storage)
Fuel cells and microfabricated fuel cells
Micro fuel cells and micro batteries
Electromagnetic storage
Explosively driven magnetocumulative generators
Batteries and supercapacitors
Thermophotovoltaics
Medium Priority Technologies
Thermoelectrics and micro thermoelectrics
Micro engines
Radioisotopic generators
Micro photovoltaics
Piezoelectrics
Mechanical storage
Low Priority Technologies
Fission
Solar
Wind
Water
Magnetohydrodynamics
Fusion

2 RECOMMENDATIONS FOR A FUTURE R&D PROGRAM IN ADVANCED POWER SOURCES

2.1 Introduction

Military technology is evolving rapidly and the introduction of many of these new technologies into service will be dependent on suitable power sources being available. For example, a dramatic increase in power source energy density is required to meet future soldier system and autonomous vehicle requirements; the development of micro power sources is needed for powering MEMS sensors and actuators; and very high power pulse sources are needed for new weapon technologies plus protection from them. Our Allies have recognized the importance of R&D into advanced power sources. DARPA, for example, has recently initiated several programs in this area. In spite of this activity, the establishment of a stronger R&D program is justified, partly because some CF requirements (e.g. low temperature performance) are not expected to be adequately addressed by our Allies and partly because of the very strong Canadian industrial expertise that exists in some power source areas. Canada has world-class industrial capability in some areas such as fuel cells (Ballard Power Systems and Hydrogenics), lithium batteries (Eagle Picher Energy Products, Hydro Quebec and Electrofuel) and thermoelectric generators (Global Thermoelectric). DND sponsorship has played an important role in the development of some of these programs (e.g. the fuel cell technology at Ballard Power Systems). In general, most power source technologies are dual-use and successful development can have wide economic benefit.

In this section of the report, we propose an expanded Advanced Power Source R&D program. The proposed program draws on expertise that already exists in DRDC and RMC as well as in other government departments such as the NRC and NR Canada, plus Canadian industry and universities. The proposed program has a strong emphasis on materials technologies.

2.2 Outline of the Proposed APS Program

It is proposed that the R&D program in Advanced Power Sources should consist of the following major elements:

1. Materials and Manufacturing Technology for Fuel Cells and Batteries
2. Hydrogen Storage and Production Technology
3. Pulse Power Technologies

The following is a more detailed breakdown of the R&D activity that is envisaged in each of these major program areas.

2.2.1 Materials and Manufacturing Technologies for Fuel Cells and Batteries

Specific areas to be investigated in this area include:

2.2.1.1 Microfabrication of Micro and Macro Power Sources

- fabrication of micro fuel cells and micro batteries for powering distributed sensors and actuators
- use of microfabrication techniques for the development of direct methanol fuel cells. Use of microfabrication should improve low temperature performance and increase efficiency by reducing methanol cross-over problems.

2.2.1.2 Nanomaterials in Batteries

- improvement of the low temperature performance of lithium batteries through the use of nanomaterials to increase surface area.

2.2.1.3 Fuel Cell Electrocatalyst Development

- improved electrocatalysts for direct methanol fuel cells to improve low temperature performance and reduce poisoning.
- battlefield contaminant resistant electrocatalysts for polymer electrolyte fuel cells.

2.2.1.4 Polymer and Solid Electrolyte Development

- improvement of the conductivity of polymer electrolytes in low humidity conditions for micro fuel cells
- improved electrolytes capable of temperature cycling for solid oxide fuel cells

2.2.2 Hydrogen Storage and Production

2.2.2.1 Storage of Hydrogen in Nanomaterials

- storage of hydrogen in carbon nanotubes and other nanomaterials

2.2.2.2 Compact Hydrogen Production Methods

- compact hydrogen production from chemical hydrides. The development of a compact hydrogen production technique for use with small, high energy density fuel cells is required. Low temperature start-up and operation need to be addressed.

2.2.2.3 Production of Hydrogen from Liquid Fuels

- the development of compact systems capable of producing hydrogen for fuel cells from liquid fuels is required. Use of logistic fuels is desirable.

2.2.3 Pulse Power Technologies

2.2.3.1 High Power Pulse Forming Networks

- compact pulse forming networks capable of delivering GW pulses for kinetic energy and radio frequency weapons and providing power for reactive armor is required.

2.2.3.2 Explosively Driven Magnetocumulative Generators

- development of very compact pulse power sources for powering RF munitions and other devices is required.

2.3 Delivery Timeframe

While the proposed APS R&D program given above (section 2.2) outlines the main tasks that could be carried out in each focus area, an estimate for the time of delivery of the results is not given. A proposed delivery timeframe for the various tasks is shown in Table 24. It is seen that the tasks that have been defined for each R&D focus include work that will be delivered in the short term (1-3 years), mid-term (4-6 years) and long term (6-9 years). Table 25 shows the linkages that exist between the various power source requirements and the various R&D tasks as well as the delivery timeframe for these tasks. It is seen that the proposed program has relevance to essentially all requirement areas.

Table 24: Timeframe for Delivery of S&T Opportunities

R&D Focus	S&T Opportunities	Delivery Timeframe		
		Short	Mid	Long
Materials and Manufacturing Technologies for Batteries and Fuel Cells	Microfabrication of Micro and Macro Power Sources			
	- Improved power density and LT performance of direct methanol fuel cells		X	
	- Micro fuel cells and batteries for MEMS sensors and actuators			X
	Nanomaterials in Batteries and Fuel Cells			
	- Lithium pouch batteries functional to -40 °C	X	X	
	- Lithium battery/supercapacitor hybrids for high power applications			
	Fuel Cell Electrocatalyst Development		X	
	- Battlefield contaminant resistant electrocatalysts for PEM fuel cells		X	
	- Improved low temperature performance and increased power density of direct methanol FC	X		
	- CO tolerant catalysts for PEM fuel cells			
	Solid Polymer and Ceramic Electrolyte Development			X
	- Increased efficiency of direct methanol FC by reducing methanol cross-over		X	
	- Solid oxide fuel capable of using logistic fuels for tactical power			
Hydrogen Storage and Production	Storage of Hydrogen in Nanomaterials			
	- High energy density hydrogen storage for soldier system and AIP requirements			X
	Compact Hydrogen Production Methods			
	- Chemical hydride generator for compact PEM fuel cell for soldier system	X		
	- Compact hydrogen generator capable of low temperature operation and rapid start-up		X	
	Production of Hydrogen from Liquid Fuels			
	- AIP demonstrator using methanol reformation	X		X
	- Hydrogen production from logistic fuels (Diesel/JP4)			
Pulse Power Technologies	High Power Pulse Forming Networks			
	- Pulse power demonstration system for All-Electric vehicle	X		
	- Impedance matching/load switching of PFN to KE and RF loads		X	
	Explosively driven magnetocumulative generators			
	- Compact EMG development	X		

Table 25: Linkages of Power Source Requirement to S&T Opportunities and Delivery Timeframe

Requirement	Power Source Options	S&T Opportunities	Delivery Timeframe		
			Short	Mid	Long
Power for Sensors and Actuators	- Micro Batteries - Micro Fuel Cells - Micro TEG - Micro TPV Generator - Piezoelectric	- micro fuel cells and batteries for MEMS sensors and actuators			X
Integrated Wearable Power	- DMFC - Hydride Fueled PEMFC - TPV Generator - Micro Engine	- improved power density and LT performance of direct methanol fuel cells		X	
		- increased efficiency of direct methanol FC by reducing methanol cross-over			X
		- high energy density hydrogen storage for soldier system and AIP requirements			X
		- chemical hydride generator for compact PEM fuel cell for soldier system	X		
Portable Power	- Primary Batteries - Secondary Batteries - DMFC - Hydride Fueled PEMFC	- lithium pouch batteries functional to minus 40 °C		X	
		- lithium battery/supercapacitor hybrids for high power applications	X		
Miniature Robotics	- Batteries - Fuel Cells - Microfabricated Fuel Cells - TPV Generator - Micro Engine	- improved power density and LT performance of direct methanol fuel cells		X	
		- increased efficiency of direct methanol fuel cells by reducing methanol cross-over			X
Mounted Power	- Engine Generators - Diesel Fueled SOFC - PEM Fuel Cell - Solar/Battery	- battlefield contaminant resistant electrocatalysts for PEM fuel cells		X	
		- CO tolerant catalysts for PEM fuel cells	X		
		- SOFC capable of using logistic fuels for tactical power		X	
		- compact hydrogen generator capable of low temperature operation and rapid start-up		X	
		- hydrogen production from logistic fuels (Diesel/JP4)			X
Aerospace Power	- Secondary Batteries - Primary Batteries - Fuel Cells	- high energy density, high rate batteries for aircraft		X	
		- high energy density lithium batteries		X	

Remote Power	- Batteries	- improved rechargeable batteries for solar energy storage			X
	- Photovoltaic Hybrid Systems	- improved efficiency thermoelectric materials		X	
	- Thermoelectric Generators	- liquid fueled thermoelectric generators for remote applications	X		
Vehicle Propulsion	- Engines	- battlefield contaminant resistant electrocatalysts for PEM fuel cells		X	
	- Diesel Fueled SOFC	- SOFC capable of using logistic fuels for tactical power		X	
	- PEM Fuel Cells	- compact hydrogen generator capable of low temperature operation and rapid start-up		X	
	- Hydrogen Storage	- hydrogen production from logistic fuels (Diesel/JP4)			
	- Diesel Reforming	- pulse power demonstration system for all-electric vehicle	X		X
	- Secondary Batteries	- CO tolerant catalysts for PEM fuel cells	X		
	- Pulse Power	- AIP demonstrator using methanol reformation	X		
Central Power	- Hydro	- SOFC capable of using logistic fuels for tactical power		X	
	- Nuclear	- hydrogen production from logistic fuels (Diesel/JP4)			X
	- Magnetohydrodynamics				
	- Renewable Energy Sources				
Pulse Power	- Mechanical Energy Storage		X		
	- Electrical Energy Storage	- impedance matching/load switching of PFN to KE and RF loads			
	- Explosive Magnetocumulative Generator	- compact EMG development		X	
	- Piezoelectric Pulse Generators	- impedance matching/load switching of PFN to KE and RF loads	X		
				X	

2.4 R&D Expertise

DRDC has existing expertise in each of the technology areas proposed that can be used as a base for the development of the expanded Advanced Power Source R&D program that has been proposed above. In addition there is also substantial expertise in Canadian industry, universities and government that can be called upon for program expansion. A summary of the existing DRDC expertise, as well as other Canadian expertise, is given in Table 26.

Table 26: R&D Expertise Available for Program Development

Program Element	Existing DRDC Activity	Potential Partners
Materials and Manufacturing Technologies for Fuel Cells and Batteries	DREA - electrochemical power sources	Canadian Industry - Fuel Cell/Battery - Microelectronic Government - RMC - NRC - NRCan Universities - various
Hydrogen Storage and Production	DREV - nanomaterials	Canadian Industry - Fuel Cell/Electrolyzer Government - RMC - NRC - NRCan Universities - various
Pulse Power Technologies	DREV- EMG technology DREO - EMG technology	Canadian Industry - MREL Government - NRC Universities - various

In order to conduct the proposed program, additional in-house personnel and financial resources will be required.

2.4.1 Linkages to DRDC TIS Activities

The proposed R&D program in Advanced Power Sources has linkages to the following DRDC R&D activities:

1. Autonomous Intelligent Systems
2. Chemical/Biological/Radiological Threat Assessment and Detection
3. Command and Control Information Systems
4. Communications
5. Electro-Optical Warfare
6. Emerging Materials and Bio-Molecular Technology
7. Multi-Environmental Life Support Technologies
8. Operational Medicine
9. Platform Performance and LCM
10. Precision Weapons
11. RF Electronic Warfare
12. Sensing (Air and Surface)
13. Sensing (Underwater)
14. Space Systems
15. Weapons Effects

2.5 Organizational Change Recommendations

There are also opportunities for improving the introduction and management of advanced power sources in the CF. To minimize the risk of fielding wrong power sources to the theatre and to have the ability to provide emergency response, sound management and knowledgeable personnel on advanced power sources are required. It would be advantageous to establish a Tri-Service Advanced Power Sources Knowledge Centre within DND consisting of scientists, engineers, logisticians, and life cycle managers to advise the departmental staff and execute APS projects of CF interest and to coordinate the effort for the CF to achieve efficiency and cost effectiveness. This would involve not only DRDC but the whole department.

2.6 Summary

In order to satisfy DND requirements out to the year 2020, R&D is needed on Advanced Power Sources to meet the power demands in the following ten areas:

- sensors and actuators.
- integrated wearable power
- portable power
- miniature robotics
- mounted/mobile power
- aerospace power
- remote power
- vehicle propulsion
- central power;
- pulse power

Seven technology areas have been identified as needed to meet the power sources requirements of these ten areas and which are considered high priority for DRDC to invest in. These are:

- chemical storage of hydrogen
- fuel cells
- micro fuel cells and micro batteries
- electromagnetic energy storage
- explosively driven magnetocumulative generators
- batteries and supercapacitors
- thermophotovoltaics

Further technologies were also identified, which were assigned medium or low priority. Some of these should also be supported subject to funding. DND already has in-house expertise in several of these seven high priority technology areas, scattered throughout the different establishments.

It is proposed that the present power sources program should be expanded and should concentrate on the following three general areas of research:

- materials and manufacturing technologies for fuel cells and batteries
- hydrogen storage and production
- pulse power.

Various short, medium and long-term tasks associated with each of these areas have been identified. The program is expected to include collaboration with other government agencies, Canadian industry and potential partners that have been identified..

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GLOSSARY

AC	Alternating Current
AECL	Atomic Energy Canada Limited
AECV	All Electric Combat Vehicle
AES	All Electric Ship
AFC	Alkaline Fuel Cell
AIP	Air Independent Propulsion
AM	Air Mass
APS	Advanced Power Sources
APV	Armored Personnel Vehicle
C^4ISR	Communication, Command & Control, Computers, Intelligence, Surveillance and Reconnaissance
CF	Canadian Forces
CFB	Canadian Forces Base
CHP	Combined Heat and Power
CJTL	Canadian Joint Task List
CNPS	Compact Nuclear Power Source
COTS	Commercial of the Shelf
DC	Direct Current
DERA	Defence Engineering and Research Agency
DMFC	Direct Methanol Fuel Cell
DND	Department of National Defence
DREO	Defence Research Establishment Ottawa
DREV	Defence Research Establishment Valcartier
EFAB	Electrochemical Fabrication
EM	Electro Magnetic
EMG	Explosive-driven magnetocumulative Generator
EO	Electro Optical
EPSG	Electrochemical Power Sources Group
ETC	Electrothermal Chemical
Etc.	Et cetera
EV	Electric Vehicle
FCC	Force Components of Capabilities
GPHS	General Purpose (Isotopic) Heat Source
GPS	Global Positioning System
HADCS	High Arctic Data Communications System
HMMWV	High Mobility Multipurpose Wheeled Vehicle
HPM	High Power Microwave
HTS	High Temperature Superconductor
i.e./e.g.	For example
IC	Integrated Circuit
ICE	Internal Combustion Engine
IEA	International Energy Agency
ISO	International Standardization Organization
KE	Kinetic Energy
LAV	Light Armored Vehicle
LT	Low Temperature

LTS	Low Temperature Superconductor
M/G	Motor/Generator
MCFC	Molten Carbonate Fuel Cell
MDS	Magnetodynamic Storage
MEA	Membrane Electrolyte Assembly
MEMS	Micro Electro-Mechanical System
MHD	Magneto Hydrodynamic
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NNEMP	Non-Nuclear Electromagnetic Pulse
NRC	National Research Council
NRCan	Natural Resources Canada
O&M	Operation and Maintenance
OGD	Other Government Departments
PAFC	Phosphoric Acid Fuel Cell
PEMFC	Proton Exchange Membrane or Polymer Electrolyte Membrane Fuel Cell
PERD	Program of Energy Research and Development
PFN	Pulse Forming Network
PLB	Personal Locator Beacon
PMO	Project Management Office
PV	Photovoltaic
PVDF	Polyvinylidenefluoride
PZT	Lead Zirconate Titanate
R&D	Research and Development
RAM	Rechargeable Alkaline Manganese
RF	Radio Frequency
RMA	Revolution in Military Affairs
RMC	Royal Military College
RTG	Radioisotope Thermoelectric Generator
RTO	Research and Technology Organization
S&T	Science and Technology
SCP	Strategic Capability Planning
SOFC	Solid Oxide Fuel Cell
SPFC	Solid Polymer Fuel Cell
SWNT	Single Wall Nano Tube
TCCCS	Tactical Communications, Command and Control System
TEG	Thermoelectric Generator
TMI	Technology Management Incorporate
TPV	Thermophotovoltaic
UAV	Unmanned Aerial Vehicle
UK	United Kingdom
UN	United Nations
US/USA	United States of America
USC	University of Southern California
VPL	Virtual Presence Limited
vs.	versus
ZT	Figure of Merit

APPENDIX
TO T3R&O ON
ADVANCED POWER SOURCES

EVALUATION OF

POWER SOURCE TECHNOLOGIES

AND

IDENTIFICATION OF R&D OPPORTUNITIES

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INTRODUCTION

In order to give the reader the possibility to follow our evaluation process in detail, we have added our considerations in this appendix to the main document. For the power requirements of each military application, please refer to chapter 2.

1 POWER FOR DISTRIBUTED SENSORS AND ACTUATORS

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

Power source technologies having the potential to meet some of the applications listed above include:

a) Microbatteries

Microbatteries can provide an efficient and flexible method of providing power to MEMS devices. The batteries need, however, to be small in size so they can be integrated with the MEMS device and they also need to have high power and energy densities. The battery must have sufficient capacity to meet the energy demands although capacity requirements can be minimized if the battery is coupled with an environmental source of energy such as solar, thermal or kinetic. Energy can be scavenged from the environment during off-duty periods and stored in the battery for use later on.

b) Micro Fuel Cells

One of the main disadvantages of the microbatteries is the limited amount of energy that each micro battery can store. This severely limits the duration that the battery can provide power to a MEMS device before recharging is necessary. Unlike batteries, fuel cells are not energy storage devices but energy converters. Provided that fuel (usually hydrogen) is fed to the fuel cell, the energy that can be produced by the cell is essentially unlimited. With the fuel cell, the electrical interconnections are replaced by gas (fuel) distribution channels. This reduces electrical noise and cross-talk problems.

c) Micro Engines

Micro engines also have the potential for providing power to MEMS devices. They can be fabricated using silicon micromachining techniques. Gaseous fueled systems appear most practical. In some applications, it may be possible to harvest hydraulic energy available from the environment using a microturbine to power microactuators or sensors. Boundary layer control or smart bearings are such applications.

d) Micro Thermoelectric Generators

The use of micro thermoelectric devices to harvest thermal energy from low-grade environmental heat sources appears to be attractive for some sensor and actuator applications.

e) Micro Photovoltaics

The harvesting of electromagnetic energy that is available from the sun or from interior lighting is attractive for powering MEMS devices. Because of the unreliable nature of solar sources, a hybrid system that also incorporates a micro battery for energy storage will probably be used.

Filter # 2: Identification of Capability Gaps.

At the present time MEMS devices are powered almost exclusively by macroscopic power sources. The use of a single macroscopic power supply to power a large number of micro sensors or actuators causes a number of problems. Distribution of power from a central source causes problems with layout efficiency in the silicon wafer and with electrical noise as a result of stray capacitance and cross talk between power and signal lines. In addition, there is a problem in controlling the power that is delivered to individual components.

To optimize the usefulness of MEMS devices, the next step in their development is to integrate a micro power source with each MEMS. This alternative would enable the development of a truly integrated system that communicates through information exchange only rather than through the exchange of information and power. In addition, the use of a micro power supply for each MEMS device permits local control of the power to each component, thus reducing control system complexity. Other advantages should include lower noise, better power efficiency and higher speed of operation.

Micro power sources that can be integrated with micro sensor networks are going to be needed in many future applications.

Filter # 3: Issues

The low acoustic and reduced thermal signature is desirable for battlespace sensor and actuator systems. This will make fuel fired power sources less attractive because of their thermal and acoustic signature.

Micro power sources are at an early stage of development. The power and energy requirements vary greatly amongst the various applications. If a microbattery is used, the battery must have sufficient capacity to meet the energy demands although capacity requirements can be minimized if the battery is coupled with an environmental source of energy such as solar, thermal or kinetic. Energy can be scavenged from the environment during off-duty periods and stored in the battery for use later on.

Filter # 4: Is there a Canadian Niche?

Canada has a strong microfabrication, battery and fuel cell base in both industry and university that could form the basis for power MEMS development in this country. Two Canadian firms, Nortel Corp. and JDS Uniphase are among the major world players in the MEMS area. A number of Canadian universities have facilities that can be used for MEMS fabrication.

Canada has a number of world-class advanced battery and fuel cell companies. In the fuel cell area, Ballard Power Systems in Vancouver is the world leader in the development of proton exchange membrane (PEM) fuel cells. In the battery area, Hydro Quebec is a world leader in the development of lithium/polymer batteries. Lithium ion batteries are being developed by Electrofuel Inc. in Toronto and by Eagle Picher Energy Products in Vancouver.
The technology is of strong interest for both military and civilian applications.

Filter # 5: Is Relevant R&D being Done by Others?

DARPA is sponsoring the development of a number of MEMS based micro power sources as part of their MEMS program.

Filter # 6: Analysis of S&T Opportunities

The elements necessary to initiate an R&D program in the power MEMS area are present in Canada. Collaboration between expert groups in microfabrication and power source technology seems to be needed. Because of Canada's strong industrial base in the battery and fuel cell areas, initiation of a program in the micro battery and/or micro fuel cell area would seem to be most fruitful. The expertise of Global electric could be called upon to develop micro TEGs however.

The following are potential research opportunities that have been identified in the power MEMS area:

a) **Development of Micro Batteries.** It appears as if many micro sensor and actuator applications will need to incorporate a micro battery to provide autonomous power. For short term, low power applications, a micro battery may have sufficient capacity to act as a stand-alone power source. In many applications, however, the prime source of energy may be an environmental source such as solar or thermal energy. In these cases, it can be anticipated that a micro battery will still be included to provide storage capacity when the environmental source fluctuates, to meet peak power demands and to smooth power fluctuations.

Because of its potentially high energy density, work in this area should concentrate on the development of lithium micro batteries. Polymer or solid electrolyte systems appear particularly attractive because of their compatibility with micro fabrication techniques. A multi-disciplinary research group that consists of experts in both microfabrication and battery electrochemistry area is needed to carry out this project. Canada has strong expertise in both areas in both industry and university to initiate such a project. This area of research has potential commercial applications as well.

b) **Development of Micro Fuel Cells.** An advantage that fuel cells have over batteries is that, in a fuel cell, the power and energy requirements can be decoupled. For long periods of operation, the energy density of the fuel cell approaches that of the fuel that can be very high. The fuel cell will provide power as long as it is fed fuel. With an array of fuel cell powered sensors, a central source of fuel could be used with the fuel being fed through micro channels etched into the silicon substrate

Solid polymer electrolyte systems appear particularly attractive because of their compatibility with micro fabrication techniques and low temperature of operation. A multi-disciplinary research group that consists of experts in both microfabrication and fuel cell electrochemistry area is needed to carry out this project. Canada has strong expertise in both Industry and University to initiate such a project.

c) **Development of Micro Thermoelectric Generators:** The scavenging of thermal energy from the environment may provide a means of powering low power, distributed sensors. In general, the temperature of available sources and sinks will be low. The development of low temperature, micro TEGs is worth consideration. Significant progress in raising the figure-of-merit of TEG materials is being made.

A multi-disciplinary research group that consists of experts in both the microfabrication and TEG area is needed to carry out this project. Global Thermoelectric gives Canada world-class expertise in the TEG Industry.

2 POWER FOR THE SOLDIER SYSTEM

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

From the information given in Chapter 3, the following power source technologies are considered to have potential for meeting the soldier system requirements.

a) Fuel Cells and Microfabricated Fuel Cells

The soldier system requirements could potentially be met by a small fuel cell. The best fuel cell options are the use of a PEM fuel cell with a high energy density hydrogen source or a direct methanol fuel cell. The use of microfabrication techniques may help to significantly raise the power density of these fuel cells. This is expected to be especially important for the direct methanol fuel cell where the current densities may be expected to be low. For long term operation, the energy density of a small fuel cell could approach 3000 Wh/kg.

b) Thermophotovoltaic Generator

TPV generators have a number of potentially attractive characteristics that make them suitable for meeting military power requirements. These include: no moving parts, which makes them inherently quiet, and they are capable of using logistic fuels. The maximum TPV efficiency is approximately 17% at the moment with projections that this may rise as high as 30% in the future. For long term operation, the energy density of a TPV power source could approach 4000 Wh/kg.

c) Micro Engines

Micro engines could potentially be used to provide a compact high energy density power source for the soldier system. Based on 10% efficiency, an energy density approaching 1300 Wh/kg is achievable.

Filter # 2: Identification of Capability Gaps.

a) Fuel Cells

The PEMFC has been well developed for a variety of applications. In order to produce a high energy density, compact power source suitable for the soldier system, development of a high energy density hydrogen source is required. The most suitable hydrogen source appears to be one that utilizes an alkali metal hydride such as calcium hydride or sodium borohydride. Improvements in the density of physically stored hydrogen through the use of carbon nanotubes may also provide a suitable source. Engineering will be required to meet CF low temperature requirements. Specific aspects that need to be addressed include system start-up and water management at low temperature.

The direct methanol fuel cell appears to be an extremely attractive option for powering the soldier system. Aspects that need investigation include improvement of the power density, elimination of poisoning as a result of partial oxidation of the methanol, reduced efficiency as a result of methanol cross-over and problems associated with low temperature start-up and operation.

b) Thermophotovoltaic Generators

Significant improvements need to be made in TPV technology to meet this requirement. These gaps include: improvement of system efficiency, development of mini-combustor technology and system integration.

c) Micro Engines

Micro engines are at an early stage of development. One of the major problems associated with the development of micro engines is the development of micro combustion systems. In small systems, heat loss to the walls becomes a much more significant problem and combustion may be hard to sustain. Catalytic combustion may be a possible solution to combustion difficulties. Engine life and system efficiency are major challenges this technology must face.

Filter # 3: Issues

Fuel cells offer the promise of high energy density and low acoustic and thermal signature. Fuel cells are inherently very simple devices with few moving parts. Low temperature operation may be a problem. Non-logistic fuels are required.

TPVs are direct conversion devices that usually have few moving parts. The low acoustic and reduced thermal signature of TPVs gives them an advantage over competing technologies such as microturbines, however the thermal and acoustic signatures are expected to be higher than that of a fuel cell system. TPVs have the potential to have a much higher energy density than existing batteries.

The risk associated with the development of a micro engine power source for powering the soldier system is high. The thermal signature is expected to be high because of the high exhaust temperature. Development of a miniature liquid fuel combustor will be difficult. Gaseous fuels are preferred.

Filter # 4: Is there a Canadian Niche?

Canada has a strong fuel cell base in both industry and university that could form the basis for both PEMFC and DMFC development in this country. In addition, there is strong expertise in the microfabrication area that could be used for the microfabrication of macro fuel cells.

Global Thermoelectric is a world leader in the development and manufacture of thermoelectric systems. Because of technology similarities, this company could be used as the basis for the development of TPV systems. There is expertise at IESVic in micro TPVs.

There is no known Canadian expertise in the micro engine area.

Filter # 5: Is Relevant R&D being Done by Others?

There are many strong programs in Canada and throughout the world aimed at the development of miniature fuel cells for powering consumer electronics. While many of the civilian requirements are similar to those of the soldier system, there are also noticeable differences. Most noticeable are the severe low temperature requirements for military systems and the need to operate in a contaminated environment.

The US ARO and DARPA have strong programs aimed at the development of TPV generators.

The US DoD is sponsoring the development of a variety of power source options to meet their soldier system requirement.

Filter # 6: Analysis of S&T Opportunities

a) Proton Exchange Membrane Fuel Cell (PEMFC)

The Proton Exchange Membrane Fuel Cell has the potential to be used in a wide range of applications, if hydrogen storage issues can be resolved. Research on the fuel cell stack itself is still progressing slowly with most of research being done by industry and academia. Areas requiring direct DRDC investment include:

4) Development of better catalysts to lower risk of fuel cell exposure to battlefield contaminants which could poison the fuel cell.
5) Improved hydrogen storage issues that directly impact on the military use of fuel cells.
6) Improved performance parameters for military specific including start-up and water management at low temperatures.

b) Direct Methanol Fuel Cells (DMFC)

The Direct Methanol Fuel Cell appears to be the most promising option as a battery replacement for applications such as powering portable electronic devices (such as cellular phones) and for the soldier system. Because of the anticipated direct industrial investment many technological issues will be solved by industry. However, DRDC investment will be needed in several topics to exploit this system for military equipment. The following are areas that will require DRDC investment:

1) Improved efficiency and materials for low temperature operation of DMFC (needed if they are to replace military batteries down to – 40 °C)
2) Find electrocatalysts that would enhance the electrode kinetics, minimize the poisoning, optimize the structure of the electrodes and the operating conditions, and improve design and construction of the electrochemical multi-stack
3) Exploring use of logistic fuels (diesel) in direct fuel cells

c) Thermophotovoltaic Generators

TPV generators have the potential to substantially improve energy density for the provision of power for the soldier in the field and to reduce acoustic signatures. These systems should help overcome the limitations of existing batteries.

While there is limited direct expertise in the TPV area in Canada, there are many similarities in the materials, fabrication and burner designs needed for TPV systems and those needed for thermoelectric systems. Global Thermoelectric is a world leader in the development and manufacture of thermoelectric systems. This expertise could be used as the base for the development and manufacture of TPV systems in Canada. Consideration could be given to initiating the development of small TPVs to meet the soldier system requirement if resources are available.

3 PORTABLE ELECTRONICS

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

From the information given in Chapter 3, the following power source technologies are considered to have the potential for meeting the power requirements for portable electronic systems.

a) Primary Batteries

Portable batteries are likely to remain the power source of choice for many short duration missions (24-48 hours) because they are simple, relatively cheap and have no thermal or acoustic signature. Beyond that time, the weight of carrying additional batteries can be a problem. Lithium-sulphur dioxide batteries are in widespread use in CF. This battery is used to power night vision goggles, combat radios, hand-held chemical agent monitors, GPS, laser sight, and emergency beacons/radios. The cells have high energy and power densities and can operate down to –50 °C.

b) Secondary (Rechargeable) Batteries

For training missions, rechargeable batteries are often used, along with the means for recharging them.

c) Fuel Cells

The Direct Methanol Fuel Cell appears to be the most promising option as a battery replacement for powering portable electronic devices. If hydrogen storage problems can be solved, the use of a small PEMFC is also an option.

Filter # 2: Identification of Capability Gaps.

a) Batteries

A range of primary and secondary batteries are available that can meet the portable electronic requirements. In the last 20 years, the major development has been the development of the lithium battery systems some of which provide high energy density and excellent low temperature performance. The cost associated with the use of lithium primary batteries is high and for this reason the US and other Allies are moving toward the use of rechargeable systems. At the present time these new rechargeable systems are incapable of providing the required CF low temperature performance. Research is needed to either improve low temperature performance or introduce a hybrid battery/ supercapacitor system to meet pulse power requirements.

b) Fuel Cells

The Direct Methanol Fuel Cell appears to be the most promising as a battery replacement for powering portable electronic equipment. This system is still at an early stage of development and important issues such as reaction rate (power density), efficiency and catalyst poisoning need to be addressed.

The Proton Exchange Membrane Fuel Cell has the potential to be used in a wide range of applications, if hydrogen storage issues can be resolved.

Filter # 3: Issues

a) Batteries

At the present time, the CF relies extensively on the use of the lithium/sulphur dioxide system for meeting the low temperature requirement of a wide range of portable electronic equipment. The US and other Allies are moving away from this system for economic reasons. For this reason the cost of supplying Li/SO_2 batteries to the CF may become prohibitively expensive. Research into alternative systems is needed.

b) Fuel Cells

Fuel cells offer the promise of high energy density and low acoustic and thermal signature. Fuel cells are inherently very simple devices with few moving parts. Low temperature operation may be a problem. Non-logistic fuels are required.

Filter # 4: Is there a Canadian Niche?

Canada has a number of world-class advanced battery and fuel cell companies. In the fuel cell area, Ballard Power Systems in Vancouver is the world leader in the development of polymer electrolyte membrane (PEM) fuel cells. In the battery area, Hydro Quebec is a world leader in the development of lithium/polymer batteries. Lithium ion batteries are being developed by Electrofuel Inc. in Toronto and by Eagle Picher Energy Systems in Vancouver. The technology is of strong interest for both military and civilian applications.

Filter # 5: Is Relevant R&D being Done by Others?

There are many strong programs in Canada and throughout the world aimed at the development of batteries and fuel cells for powering consumer electronics. While many of the civilian requirements are similar to those of the military, there are also noticeable differences. Most noticeable are the severe low temperature requirements for military systems and the need to operate in a contaminated environment.

Filter # 6: Analysis of S&T Opportunities

a) Portable Primary Batteries

Research is needed to adapt the lithium pouch battery technology to meet CF requirements, in particular the low temperature requirement. DND should carry out research into improved electrolytes for low temperature operations by using tertiary solvent mixtures. High surface area manganese dioxide could be made using a sol-gel technique and the use of a conducting additive in the cathode could also be investigated. In addition, research should include the hybrid use of Li/MnO_2 cells with a supercapacitor to meet low temperature, pulse power requirements. Some of this work could be undertaken in collaboration with Eagle-Picher Canada. The benefit to DND would be a higher capacity battery to replace the BA5590 lithium-sulphur dioxide battery.

The potential of the zinc-iron system to meet CF requirements should also be investigated. This battery is a possible replacement for zinc-alkaline manganese dioxide batteries.

b) Portable Rechargeable Batteries

DND should carry out research into improving the high rate and low temperature performance of lithium-ion and lithium ion polymer cells through the use of alternative electrolytes or additives and by using additives to reduce the interfacial resistance of the electrodes. A hybrid system with a supercapacitor should also be considered. These cells could be modified to improve the rate and low temperature performance simply by making the electrodes more porous. Electrofuel is expected to collaborate with DND at little cost, possibly in association with US Army CECOM. DND should also investigate ways to cycle cells containing lithium metal anodes safely.

Nickel-metal hydride or lithium-ion batteries are likely to replace sealed nickel-cadmium in the long-term for communications equipment. Areas of research for DND would be novel metal hydrides for higher energy density, improving the low temperature performance, and ways of reducing self-discharging of the metal hydride and the nickel oxide electrode.

c) Fuel Cells

The Proton Exchange Membrane Fuel Cell has the potential to be used in a wide range of applications, if hydrogen storage issues can be resolved. Research on the fuel cell stack itself is still progressing slowly with most of the research being done by industry and academia. Areas requiring direct DRDC investment include:

1) Development of better catalysts to lower risk of fuel cell exposure to battlefield contaminants which could poison the fuel cell.
2) Improved hydrogen storage issues that directly impact on the military use of fuel cells.
3) Improved performance parameters for military specific applications such as high-powered soldier systems anticipated in 2020.

The Direct Methanol Fuel Cell appears to be the most promising option as a battery replacement for applications such as powering portable electronic devices (such as cellular phones) and for the soldier system. Because of the anticipated direct industrial investment many technological issues will be solved by industry. However, DRDC investment will be needed in several topics to exploit this system for military equipment. The following are areas that will require DRDC investment:

1) Exploration of the use of logistic fuels (diesel) in direct fuel cells
2) Improved efficiency and materials for low temperature operation of DMFC (needed if they are to replace military batteries down to – 40 °C)

Find electrocatalysts that would enhance the electrode kinetics, minimize the poisoning, optimize the structure of the electrodes and the operating conditions, and improve design and construction of the electrochemical multi-stack.

4 MICRO AIR VEHICLES AND MICRO ROBOTS

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

From the information given in Chapter 3, the following power source technologies are considered to have the potential for meeting the Micro Air Vehicle and Micro Robot requirements.

a) Batteries

In the short term, the requirements for this application will probably be met using high energy density lithium batteries. In the longer term a higher energy density power source is needed.

b) Fuel Cells and Microfabricated Fuel Cells

The MAV and MAR requirements can potentially be met by a small fuel cell. The best fuel cell options are the use of a PEM fuel cell with a high energy density hydrogen source or a direct methanol fuel cell. The use of microfabrication techniques may help to significantly raise the power density of these fuel cells. This is expected to be especially important for the direct methanol fuel cell where current densities may be expected to be low. For long term operation, the energy density of a small fuel cell could approach 3000 Wh/kg.

c) Thermophotovoltaic Generator

TPV generators have a number of potentially attractive characteristics that make them suitable for meeting the MAV and MAR power requirements. These include: no moving parts which makes them inherently quiet, and they are capable of using logistic fuels. At present, the maximum TPV efficiency is approximately 17% with projections that this may rise as high as 30% in the future. For long-term operation, the energy density of a TPV power source could approach 4000 Wh/kg.

d) Micro Engines

Micro engines could potentially be used to provide a compact high energy density power source for the soldier system. Based on 10% efficiency, an energy density approaching 1300 Wh/kg is achievable. The disadvantage of an engine system will be relatively high acoustic and thermal signatures.

Filter # 2: Identification of Capability Gaps.

a) Fuel Cells

The PEMFC has been well developed for a variety of application. In order to produce a high energy density, compact power source suitable for Micro Air Vehicles and Micro Robots, development of a high energy density hydrogen source is required. The most suitable hydrogen source appears to be one that utilizes an alkali metal hydride such as calcium hydride or sodium borohydride. Improvements in the density of physically stored hydrogen through the use of carbon nanotubes may also provide a suitable source. Engineering will be required to meet CF low temperature requirements. Specific aspects that need to be addressed include system start-up and water management at low temperature.

The direct methanol fuel cell appears to be an extremely attractive option for powering the soldier system. Aspects that need investigation include improvement of the power density, elimination of poisoning as a result of partial oxidation of the methanol, reduced efficiency as a result of methanol cross-over and problems associated with low temperature start-up and operation.

b) Thermophotovoltaic Generators

Significant improvements need to be made in TPV technology to meet this requirement. These gaps include: improvement of system efficiency, development of mini-combustor technology and system integration.

c) Micro Engines

Micro engines are at an early stage of development. One of the major problems associated with the development of micro engines is the development of micro combustion systems. In small systems, heat loss to the walls becomes a much more significant problem and combustion may be hard to sustain. Catalytic combustion may be a possible solution to combustion difficulties. Engine life and system efficiency are major challenges this technology must face.

Filter # 3: Issues

Fuel cells offer the promise of high energy density and low acoustic and thermal signature. Fuel cells are inherently very simple devices with few moving parts. Low temperature operation may be a problem. Non-logistic fuels are required.

TPVs are direct conversion devices that usually have few moving parts. The low acoustic and reduced thermal signature of TPVs gives them an advantage over competing technologies such as microturbines, however the thermal and acoustic signatures are expected to be higher than that of a fuel cell system. TPVs have the potential to have a much higher energy density than existing batteries.

The risk associated with the development of a micro engine power source for powering MAVs is high. The thermal signature is expected to be high because of the high exhaust temperature. Development of a miniature liquid fuel combustor will be difficult. Gaseous fuels are preferred.

Filter # 4: Is there a Canadian Niche?

Canada has a strong fuel cell base in both industry and university that could form the basis for both PEMFC and DMFC development in this country. In addition, there is strong expertise in the microfabrication area that could be used for the microfabrication of macro fuel cells.

Global Thermoelectric is a world leader in the development and manufacture of thermoelectric systems. Because of technology similarities, this company could be used as the basis for the development of TPV systems. There is expertise at IESVic in micro TPVs.

There is no known Canadian expertise in the micro engine area.

Filter # 5: Is Relevant R&D being Done by Others?

There are many strong programs in Canada and throughout the world aimed at the development of miniature fuel cells for powering consumer electronics. The US ARO and DARPA have strong programs aimed at the development of new high energy density power systems for MAVs and MARs.

Filter # 6: Analysis of S&T Opportunities

a) Proton Exchange Membrane Fuel Cell (PEMFC)

The Proton Exchange Membrane Fuel Cell has the potential to be used in this application, if hydrogen storage issues can be resolved. Research on the fuel cell stack itself is still progressing slowly with most of research being done by industry and academia. Areas requiring direct DRDC investment include:

1) Development of better catalysts to lower risk of fuel cell exposure to battlefield contaminants which could poison the fuel cell.
2) Improved hydrogen storage issues that directly impact on the military use of fuel cells.
3) Improved performance parameters for military specifics including start-up and water management at low temperatures.

b) Direct Methanol Fuel Cells (DMFC)

The Direct Methanol Fuel Cell appears to be the most promising option as a battery replacement for applications such as powering portable electronic devices (such as cellular phones) and for Micro Air Vehicles and Micro Robots. Because of the anticipated direct industrial investment many technological issues will be solved by industry. However, DRDC investment will be needed in several topics to exploit this system for military equipment. The following are areas that will require DRDC investment:

1) Improved efficiency and materials for low temperature operation of DMFC (needed if they are to replace military batteries down to – 40 °C)
2) Find electrocatalysts that would enhance the electrode kinetics, minimize the poisoning, optimize the structure of the electrodes and the operating conditions, and improve design and construction of the electrochemical multi-stack.
3) Exploring use of logistic fuels (diesel) in direct fuel cells

c) Thermophotovoltaic Generators

TPV generators have the potential to substantially improve energy density for the provision of power for the soldier in the field and to reduce acoustic signatures. These systems should help overcome the limitations of existing batteries.

While there is limited direct expertise in the TPV area in Canada, there are many similarities in the materials, fabrication and burner designs needed for TPV systems and those needed for thermoelectric systems. Global Thermoelectric is a world leader in the development and manufacture of thermoelectric systems. This expertise could be used as the base for the development and manufacture of TPV systems in Canada. Consideration could be given to initiating the development of small TPVs to meet the Micro Air Vehicle and Micro Robot requirements if resources are available.

5 MOUNTED/MOBILE POWER

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

From the information given in Chapter 3, the following power source technologies are considered to have potential for meeting the requirements for silent, mobile field power and to replace the existing engine generators that are presently being used.

a) Fuel Cells

The requirements for silent, mobile field power can potentially be met by a small fuel cell. The best fuel cell options are the use of a PEM fuel cell with a reformer to convert a liquid fuel such as methanol into hydrogen or a solid oxide fuel cell capable of utilizing logistic fuels.

b) Thermophotovoltaic Generator

TPV generators have a number of potentially attractive characteristics that make them suitable for meeting military power requirements. These include: no moving parts which makes them inherently quiet and they are capable of using logistic fuels. At the present time the maximum TPV efficiency is approximately 17% at the moment with projections that this may rise as high as 30% in the future. For long-term operation, the energy density of a TPV power source could approach 4000 Wh/kg.

c) Solar

Although not reliable enough to serve as the prime power source, the use of solar photovoltaic systems to supplement the prime power source offers the advantages of improved fuel efficiency and reduced thermal and acoustic signature.

Filter # 2: Identification of Capability Gaps.

a) Fuel Cells

The Proton Exchange Membrane Fuel Cell has the potential to be used in a wide range of military applications including that of silent, mobile electrical power. Research on the fuel cell stack itself is being done by largely by industry and academia. Areas requiring direct DRDC investment include the development of better catalysts to lower risk of fuel cell exposure to battlefield contaminants that could poison the fuel cell. Work is also required in the fuel processing and system integration areas.

To meet the military requirements for low temperature operation and high power output generators will require the development and use of materials that are more robust than those being developed for civilian applications. Industry will not invest by itself into specific military needs such as system designs and improved materials for smaller/ portable applications or the wide temperature range that military uses its power sources in.

b) Thermophotovoltaics

TPV technology has the potential of offering the military a relatively efficient, silent source of field power that is capable of operating on logistic fuels. Considerably more development work is required to demonstrate that reliable, rugged systems can be produced.

c) Solar

Solar power can become a viable alternative to primary batteries and thermoelectric generators. Canvas bonded small solar panels, when unfolded and placed at a suitable exposure angle, can provide adequate output capacity to charge tactical voice and data communication devices as well as other applications. Research is required to reduce weight, develop flexible panels that can be folded and reduce visual signature (camouflage). Integration with prime power sources is an important consideration.

Filter # 3: Issues

a) Fuel Cells

Fuel cells have the potential of offering a highly efficient, silent source of field power. The PEMFC is a low temperature fuel cell that requires a relatively pure source of hydrogen. The most promising option for fueling this system is reformation of methanol. Issues relating to the introduction of a non-logistic fuel onto the battlefield need to be considered. The SOFC operates at a much higher temperature and has the potential to use logistic fuels. Because its operating temperature is high, the thermal signature of the fuel cell may be an issue although it is expected to be lower than that of the engine generators currently in use.

b) Thermophotovoltaic Generators

TPVs are direct conversion devices that usually have no moving parts. The low acoustic and reduced thermal signature of TEGs when compared to engine generators are a definite advantage. TPVs have the potential to operate on logistic fuels and to be multifuel capable.

c) Solar

The main issue related to the use of solar is whether the benefits of being able to supplement prime power sources when solar energy is available is outweighed by the cost and weight penalties that will be incurred.

Filter # 4: Is there a Canadian Niche?

a) Fuel Cells

Canada has a strong fuel cell base both in industry and in university that could form the basis for both PEMFC and SOFC development in this country. The technology is dual use, and important economic benefits could also result from DRDC involvement in this area of research.

b) Thermophotovoltaic Generators

Global Thermoelectric is a world leader in the development and manufacture of thermoelectric systems. Because of technology similarities, this company could be used as the basis for the development of TPV systems. IESVic is conducting some research aimed at the development of micro TPVs.

Filter # 5: Is Relevant R&D being Done by Others?

Los Alamos National Lab and Jet Propulsion Lab in the US have strong PEMFC development programs. The US DoD is sponsoring work in this area. In the UK, DERA is sponsoring SOFC development. The US ARO and DARPA have strong programs aimed at the development of TPV generators.

Filter # 6: Analysis of S&T Opportunities

a) Fuel Cells

The Proton Exchange Membrane Fuel Cell has the potential to be used in a wide range of applications. Areas requiring direct DRDC investment include:

1) Development of better catalysts to lower risk of fuel cell exposure to battlefield contaminants which could poison the fuel cell.
2) Improved performance parameters for military specific including start-up and water management at low temperatures.

The military requirements for low temperature operation and high power output generators means further R&D into SOFC will provide useable units in 2010-2020 timeframe only with direct DND R&D investment into the technology. The industry currently investing in this area is more interested in exploiting the technology for large units for electricity generation. The development and use of materials that are more robust for military use, the wide temperature range that the military uses its power sources in, as well the need for system designs and improved materials for smaller/portable applications will not be invested into by industry itself. Specific topics that DRDC should address in this technology are:

3) The direct electrochemical oxidation of hydrocarbon fuels in SOFCs
4) Improvement in materials for both smaller design and cold temperature operation

b) Thermophotovoltaic Generator

TPV generators have the potential to provide an efficient, silent source of mobile electrical power with reduced acoustic and thermal signatures. These systems should help to overcome the limitations of existing engine generators.

While there is limited direct expertise in the TPV area in Canada, there are many similarities in the materials, fabrication and burner designs needed for TPV systems and those needed for thermoelectric systems. Global Thermoelectric is a world leader in the development and manufacture of thermoelectric systems. This expertise could be used as the base for the development and manufacture of TPV systems in Canada. Consideration could be given to initiating the development of small TPVs to meet the soldier system requirements if resources are available.

6 REMOTE POWER FOR COMMUNICATIONS AND SURVEILLANCE

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

a) Batteries

Within DND, large format zinc-air (air depolarized) cells have been used for many years to power the remote High Arctic Data Communications System (HADCS) and other remote sites. SAFT, the manufacturer of these large cells, is discontinuing production and DND is in the process of seeking a replacement system. As a replacement, DND has sponsored the development of the aluminum-air system. Canada has been instrumental in the development of these batteries. Initial work began with Alcan International Ltd. and the work is now carried on by Fuel Cell Technologies Ltd. in Kingston, ON and Alupower Inc. in Connecticut.

b) Photovoltaic Hybrid Systems

To alleviate the high cost of replacement of the zinc-air batteries, DND has installed photovoltaic/battery hybrid systems at all of their remote High Arctic Data Communications sites to provide power during the summer months. Experiments carried out by Diversitel Communications Inc. demonstrated that by incorporating sufficient battery and thermal storage, a photovoltaic/battery system could be used to provide power reliably for all of the year, even in the high Arctic.

c) Thermoelectric Generators

Many of the mountaintop microwave repeater stations throughout out the world use thermoelectric power. These installations are generally remote. The generators are usually propane fueled and many are only visited for annual refueling and maintenance.

Filter # 2: Identification of Capability Gaps.

Existing technology is largely capable of meeting these power requirements.

Filter # 3: Issues

TEGs are direct conversion devices that usually have no moving parts. High reliability and low maintenance are characteristics. The low acoustic and reduced thermal signature of TEGs may be an advantage from a military point of view. The possibility of harvesting thermal energy from the environment is a possibility. This could be useful for remote communication and surveillance systems.

Filter # 4: Is there a Canadian Niche?

Canada has been instrumental in the development of aluminum-air batteries. Fuel Cell Technologies Ltd. in Kingston is carrying on this work. An experimental system has been evaluated at Alert.

Diversitel Communications Inc. has experience in the design of photovoltaic systems for providing power to remote communications system. An experimental annual solar power system has been developed and evaluated at Alert.

Global Thermoelectric is the world's largest supplier of thermoelectric generators. Global has 25 years of experience in the engineering, manufacturing and installation of remote power systems.

Filter # 5: Is Relevant R&D being Done by Others?

There are many Canadian and US companies that supply power systems for the commercial market. These systems are widely used at radio repeater and cell phone sites.

Filter # 6: Analysis of S&T Opportunities

It seems probable that there will be a sufficiently strong commercial interest in this type of application that DND research activity is not required.

7 POWER FOR AN ALL-ELECTRIC COMBAT VEHICLE

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of power sources options

From the information given in chapter 3, the following power source technologies are considered to have the potential for meeting the AECV requirements.

Basic Power Supply

a) Combustion engines with permanent magnet excited generators

The basic power supply could be provided by an improved diesel engine with an attached PM generator that provides enough energy to run the vehicle's hub motors and at the same time charge the main storage fast enough to provide enough energy for the planned mission profiles. This would be the conservative option in supplying an AECV with energy.

b) Fuel Cells

The power requirements of an AECV could be met by fuel cells. Especially when using a PEMFC, there are the advantages of low signatures (IR, acoustic, exhaust). An also important issue with fuel cells is the fuel storage, depending whether pure hydrogen is used or methanol through a reformer. To avoid introducing another logistic fuel, it might be advantageous to run the fuel cells on hydrogen reformed from diesel, but all reformer technologies cause IR and exhaust signatures. Another possibility is the direct methanol fuel cell which would need another logistic fuel but one that is rather easy to handle.

Main Storage

a) Magneto-dynamic storage

The requirements for the main storage could be met by a flywheel storage. It is a rather mature technology and provides relatively high power and energy densities. It can store enough energy for several shots with an electric weapon (at the moment at least for an ETC gun) and can provide enough power to recharge a pulse power supply for the weapon input.

b) Supercapacitors

Another possibility for the main storage are supercapacitors. As they have no moving parts, they would be a quiet and low signature storage. They could also replace, if the basic power supply is an combustion engine, the starter batteries. Their usability is limited by the pulse power supply: if the pulse forming network is made of capacitors, it is not very advantageous to use supercapacitors to recharge them.

Pulse Power Supply

The pulse power supply is a pulse forming network that contains relatively little energy but can provide a high power output to meet the requirements of an electrical weapon.

a) Capacitors

Capacitors with their high power output could serve as power supply in a pulse forming network. Up to now, their energy density still needs improvement to make them small enough to store the energy for one shot and still fit into an AECV.

b) Superconducting Storage

Superconducting coils are an alternative to capacitors in a pulse forming network. Their problem is the cryogenic environment that they need. Although some research has been done in developing high temperature superconductors, there has to be a breakthrough before superconducting storage becomes an alternative in an AECV.

Filter # 2 Identification of Capability Gaps

a) Combustion Engines

Combustion engines with permanent magnet excited generators
Combustion engines are well developed for all kinds of purposes. For an electric driven AECV their speed is independent from their momentum and the engine can therefore be optimized for low fuel consumption. As this is an old mature technology, there are no capability gaps.
As for the permanent magnet excited generators, the technology is also rather well developed although new materials for power electronics are investigated to improve power density.

b) Fuel Cells

The PEMFC has been well developed for a variety of applications, but still its power and energy density are not high enough to be serve as basic power supply on an AECV. Another major problem is the hydrogen supply. Diesel or methanol reformers are not yet developed to a level that allows integration into a combat vehicle, neither are other hydrogen storage technologies like nanomaterials, metal hydrides or compressed gas tanks.

c) MDS

The magneto-dynamic storage has been in use on civilian buses for quite some time now. Their technique is pretty mature although it would be advantageous to find materials that would allow higher rotating speeds in order to increase their energy and power density. They need to be ruggedized for military applications but this should not be too much of a problem.

d) Supercapacitors

Although quite some improvements have been made there is still a need for advances. To be comparable with the MDS their power and energy density has to increase by a factor of about 4.

e) Capacitors

Also the capacitors for the pulse forming network need some significant improvement in their power and energy density. New materials have to be investigated to meet the requirements of the pulse power supply.

f) Superconducting Storage

Superconducting energy storages are the ideal way of storing electric energy because no transformation between different forms of energy is needed. The problem with this type of storage is to provide the necessary cryogenic environment. Most superconducting materials require temperatures about 4 K (temperature of liquid helium) to acquire their unique properties. This means too much additional equipment which does not fit onto an AECV. New materials that are superconducting at higher temperature levels (e.g. at the temperature of liquid nitrogen ~75 K) are needed to reduce cryogenic efforts to a reasonable amount.

Filter # 3 Issues

Fuel cells promise to offer sufficient energy to serve as a basic energy source on an AECV. They will also be able to serve as a charging unit for a main storage like a MDS or supercapacitor. They are simple devices with few moving parts and low signatures. Problems could occur at very low temperature levels and with the need for non-logistic fuels.

The MDS has the potential to serve very well as a main storage in an AECV. In order to uncouple the gyroscopic forces from the vehicle, it needs a cardanic suspension (like in the civil buses in which the MDS has been used) which has to be adjusted to military shock and vibration needs.

Material research is needed for the improvement of supercapacitors and capacitors as well as investigation of production methods.

Filter # 4 Is there a Canadian Niche?

Canada has a world leading industry in the development of PEMFC which are favorable for the use in mobile military application.
Canada also has a strong supercapacitor base at the university of Ottawa and the necessary expertise in this field.

Filter # 5 Is relevant R&D being done by others?

The development of the Magneto-dynamic storage has taken place in Germany. Also capacitors for the needs in a pulse-forming network have been developed there. The development of the superconducting storage for the use with electric weapons has been given up for monetary reasons.

Filter # 6 Analysis of S&T Opportunities

For S&T Opportunities for fuel cells, please refer to the Soldier System. Depending on the wish to use logistic fuels, it is necessary to invest some money in investigating the appropriate reformer technology as diesel reformers might not be developed for the civil market. Another opportunity to be ahead of development is to support materials research in hydrogen storage. New materials and production methods have to be developed in order to make fuel cells viable.
Supercapacitors cannot only power weapons and vehicles but also smaller devices like radios, goggles and GPS receivers. They might be able to replace rechargeable batteries. Their main advantage in this case would be that they could be recharged rapidly. As there is quite some expertise in Canada in this area, it would be advantageous to support this research by funding.

8 POWER FOR AN ALL-ELECTRIC SHIP

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of power sources options

Considering an All Electric Ship it is not that much a question of power sources for realization. Near-term solutions like diesel generators and gas turbines are available, and in the mid- to long term the integration of appropriate fuel cells should be no problem. As space on a ship is not as limited as on a combat vehicle, several options for different types of fuel cells are available and by the time should be developed by industry anyway. For PEMFCs it is necessary to ensure that they are not poisoned by battlefield contaminants and can work under citadel conditions. Solid oxide fuel cells might be a good choice despite their high working temperature.

Filter # 2 Identification of Capability Gaps

Major concerns in realizing an AES are material sciences and engineering challenges. For permanently excited motors and their frequency converters new materials lead to higher energy and power densities; they reduce weight and volume and even waste heat.

Filter # 3 Issues

There is a certain risk in realizing these types of motors and generators for technical reasons.

Filter # 4 Is there a Canadian Niche?

There is no known Canadian activity in this area that we are aware of.

Filter # 5 Is relevant R&D being done by others?

Several NATO allies like the US, the UK, Germany and the Netherlands are thinking about realizing an AES and therefore do some research in the above mentioned areas. Especially the US is spending a lot of money in developing electric propulsion for surface vessels.

Filter # 6 Analysis of S&T Opportunities

Canada should keep a watching brief on the activities of the allies and the involved industries. DND might get involved according to interest.

9 AIR INDEPENDENT PROPULSION (AIP) OF SUBMARINES AND SUBMERSIBLES

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of power sources options

From the information given in chapter 3, the following power source technologies are considered to have potential for meeting the AIP requirements.

a) Fuel cells

The AIP system requirements can be met by the usage of fuel cells. The best fuel cell options are PEM fuel cells. Their main advantages are:

- High efficiency, especially at partial loads
- Low noise
- Low IR signature due to low operating temperatures
- Water is the only exhaust
- Full weight compensation between reactants and exhaust product
- Functions independently from depth
- Easy to maintain
- No load control necessary
- Shock proof, little strayfield
- High lifetime expectance
- No poisoning because no air intake, oxygen is carried along

The necessary hydrogen can be stored on board or being reformed through a methanol reformer. For this reason, another advantageous option might be the direct methanol fuel cell.

b) Batteries

Even if a submarine runs on fuel cells, batteries will probably stay if only for backup reasons. Depending on the size of the fuel cell power plant, it might be necessary to get additional power from batteries for maximum speed demands. Up to now lead acid batteries have been used. Another couple that is being investigated for submarine use is nickel-metal hydride. Low temperature capabilities are not too much a concern on submarines.

c) Nuclear power

Nuclear power can only be used on large submarines like Russia and the US Navy are using. For environmental, health risk and cost issues on the one side and on the other side the positive developments on the fuel cell side it is not necessary to consider nuclear power on submarines further.

Filter # 2 Identification of Capability Gaps

a) Fuel cells

The PEM fuel cell has been developed for submarine application already. A 34 kW module will be used on the German submarine U212 and a 120 kW lab module already exists. Though an increase in energy and power density is desirable, the main concern is hydrogen storage options or reforming of methanol. This requires improvement on reformer technology because space for such equipment is very limited on a submarine. DMFC may offer another alternative.

b) Batteries

It would be desirable to use batteries with higher energy and power density. Therefore the problems related to nickel-metal hydride batteries should be solved.

Filter # 3 Issues

Fuel cells offer good performance on submarines. The main issue to be solved is hydrogen storage.

It has to be investigated whether the higher price of nickel-metal hydride batteries is justified for the advantages they offer over the mature, cheap and proven lead-acid batteries on submarines. Other battery couples based on lithium seem too dangerous in large scale applications to be considered for use on submarines.

Filter # 4 Is there a Canadian Niche?

Canada has a leading industry in PEM fuel cell development. The technology is dual use and important economic benefits could also result from DRDC involvement in this area of research.

Filter # 5 Is relevant R&D being done by others?

Germany is building the first fuel cell powered submarine at the moment, but there will be still diesel engines for charging the lead acid batteries. Friwo is investigating on nickel-metal hydride batteries for submarine but at the moment further information on this topic is not available as it is company confidential.

Filter # 6 Analysis of S&T Opportunities

Although a lot of research is done on the civilian market on hydrogen storage, investment in new materials for hydrogen storage would be a profitable area of research for several fuel cell applications.

DND should keep a watching brief on battery developments.

10 CENTRAL POWER

Evaluation of Power Source Technologies and Identification of R&D Opportunities

This requirement can be met using commercially available technology and sources. No capability gaps exist and there is no need for DRDC to conduct R&D in this area.

11 KINETIC ENERGY AND RADIO FREQUENCY WEAPONS

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

A hybrid pulse power system consisting of a prime power source and a pulse-forming network (PFN) to meet the high power requirement is the most feasible option. The low energy density of existing capacitors is a concern. Use of supercapacitors may be possible however they may not be able to meet peak power requirements.

Filter # 2: Identification of Capability Gaps.

There is a need for a lightweight very high power/energy pulse source for powering future KE and RF weapons.

Filter # 3: Issues

This is a highly classified area of research. The capability of these new weapon types is strongly dependent on the capability of the power source that is used to drive them. In order to be able to assess the potential threat of these new weapons to the CF, it is important to maintain some activity in this area.

Filter # 4: Is there a Canadian Niche?

Expertise exists in Government labs at NRC, DREV and DREO. There is some Canadian industrial expertise.

Filter # 5: Is Relevant R&D being Done by Others?

The US and many NATO countries are exploring the use of EM guns and RF weapons.

Filter # 6: Analysis of S&T Opportunities

The introduction of new KE and directed energy weapons is critically dependent on the development of very high power short duration pulse power sources. There is very limited Canadian activity in this area. Work in this area needs to be expanded.

12 RF MUNITIONS

Evaluation of Power Source Technologies and Identification of R&D Opportunities

Filter # 1 Determination of Power Source Options

a) Explosively Driven Magnetocumulative Generator

In an explosively driven magnetocumulative generator (EMG), explosives are used to compress an initially induced magnetic field by driving together some or all of the conducting surfaces that contain the magnetic flux. The work done by the moving conductor against the magnetic field results in an increase in the stored magnetic energy. The additional energy is provided by the chemical energy of the explosive.

Filter # 2: Identification of Capability Gaps.

There is a need for a pulse source for powering RF munitions.

Filter # 3: Issues

This is a highly classified area of research. The capability of these new weapon types is strongly dependent on the capability of the power source that is used to drive them. In order to be able to assess the potential threat of these new weapons to the CF, it is important to maintain some activity in this area.

Filter # 4: Is there a Canadian Niche?

Work on non-nuclear EMP is being carried out under the DRDC Technology Investment Fund program in a collaborative program led by France Beaupre, DREV, and Satish Kashyap, DREO. Dr. M. Kekez of NRC is also a major contributor to this program.

MREL, in Kingston, conduct explosives research and have the facilities and expertise needed to conduct research in the EMG area. There are also a number of University researchers that have electromagnetic expertise that could be drawn on if an EMG program were initiated. These include Dr. K. Balmain of the University of Toronto who is an expert in electromagnetic discharge and Dr. L. Shafai of the University of Manitoba who is an electromagnetics expert.

Filter # 5: Is Relevant R&D being Done by Others?

The US and many NATO countries are exploring the use of NNEMP weapons.

Filter # 6: Analysis of S&T Opportunities

EMGs are one of the few technologies capable of powering compact NNEMP. Development programs being carried out in other countries are largely "black". R&D activity in this area is needed to stay abreast in this area of directed energy technology.

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(U) In this study, the state-of-the-art and current trends in a broad range of advanced power source technologies of interest for future CF requirements has been assessed. The power source technologies examined include electrochemical power sources, electromechanical power sources, micro-electromechanical power sources, renewable energy sources, nuclear sources and energy storage technologies. The report examines the ability of these advanced power sources to meet CF requirements out to the year 2020 and identifies specific research and development opportunities that exist for DRDC. Based on these opportunities, an expanded R&D program in the Advanced Power Source area has been proposed. The principal elements of the proposed program include work in the areas of: Materials and manufacturing technology for fuel cells and batteries; hydrogen storage and production technologies; and, pulse power technologies.

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